[AMERICAN JOURNAL OF SCIENCE, VOL. 298, APRIL, 1998, P. 265–295]

American Journal of Science

APRIL 1998

RIVER SEDIMENT DISCHARGE TO THE OCEANS: PRESENT-DAY CONTROLS AND GLOBAL BUDGETS

WOLFGANG LUDWIG and JEAN-LUC PROBST

Ecole et Observatoire des Sciences de la Terre, Centre de Géochimie de la Surface (ULP/CNRS) 1, rue Blessig, 67084 Strasbourg Cedex, France

ABSTRACT. Empirical relationships between river sediment yields and a large number of hydroclimatic, biological, and geomorphological parameters are investigated at the global scale. For a set of 60 major world river basins, the environmental characteristics were extracted from various global computer data sets, and natural river sediment fluxes were taken from the literature. It is found that sediment yields can be best correlated by forming the products of hydroclimatic and geomorphological factors, that is, runoff intensity, basin slope, an index characterizing rock hardness, and an index characterizing rainfall variability over the year. The best parameter combination varies to some extent when the rivers are grouped according to their average climatic situation, but it is always a combination of the above mentioned parameters that yields the most significant models. In arid climates, however, regression coefficients are greater than in humid climates, indicating that erodibility is much greater in arid climates. When extrapolated to the total continental area on the basis of the corresponding data sets, the empirical models result in a total sediment flux of about 16 Gigatons discharged to the oceans every year, which is in good agreement with previous estimates derived from compilations of world-wide river data. Consequently, two global maps are proposed showing the spatial distributions of river sediment yields on the continents as well as the inputs of these sediments to the oceans in a grid point scale. By far most of the sediments originate from the young orogenic belts of the continents, mainly due to a combination of steep morphologies and high runoff intensities.

INTRODUCTION

The mechanical erosion of rocks and the subsequent transport of the eroded materials to the oceans by rivers is one of the principal landscape forming processes on Earth. River sediment fluxes (F_{TSS}) play an important role in various natural geochemical cycles such as the global carbon cycle. Also the transport and cycling of human released contaminants is often strongly coupled to the transport of sediment in rivers, since many contaminants have some degree of associations with the particulate phase in water (Walling and Webb, 1985; Leenheer, 1991). Beside their role in natural cycles, scientists became interested in studying sediment fluxes because of their often drastic changes due to human impacts on natural ecosystems. Modern changes in drainage basin characteristics, for example, by river damming, deforestation, or extensive cultivation, may significantly alter natural mechanical erosion rates and river sediment fluxes. Such perturbations can have severe consequences for agriculture, mainly through the loss of fertile soils. But also in the estuaries and coastal zones, where sediments end up, an alteration of the natural river sediment supply can provoke considerable changes of the metabolism in the coastal zone and/or of coastline morphology (International Geosphere Biosphere Program, 1995).

In order to assess the response of river sediment fluxes to regional and global change, an understanding of the main factors that control the fluvial sediment transport to the oceans is needed. Several attempts have been made to analyze, for example, the relationships between mechanical erosion rates and precipitation (Langbein and Schumm, 1958; Fournier, 1960; Douglas, 1967; Wilson, 1973; Ohmori, 1983). Other authors considered climate as the dominant controlling factor (Jansson, 1982, 1988), while again others pointed out the great influence of basin elevation and morphology on sediment fluxes (Schumm and Hadley, 1961; Ahnert, 1970; Pinet and Souriau, 1988; Milliman and Syvitski, 1992; Summerfield and Hulton, 1994), or they proposed multiple regression models combining various parameters to predict sediment fluxes world-wide (Jansen and Painter, 1974; Probst, 1992).

The purpose of this paper is to determine the main factors and relationships that control river sediment fluxes at the global scale. Our approach is based on a set of 60 major world rivers. The hydroclimatic, biological, geomorphological, and lithological characteristics of the drainage basins of these rivers were extracted from a large number of environmental data sets using the digitized basin contours. These characteristics were then used for regression analyses together with literature data on the observed sediment fluxes of the rivers to identify the most important controlling factors.

Many of the previous investigations suffered from strong data limitations, especially with respect to environmental parameters. The numerous global environmental data sets used in this study allow not only a very detailed description of the investigated river basins, but they also allow an easy extrapolation of empirical relationships over the continents. This is important because one can test whether these relationships agree with the observed variability of river sediment fluxes based on compilations of world-wide river data both at regional and global scales. First, we review some of the frequently cited literature models in this respect. Then we present and discuss the most significant relationships we found. We show that an extrapolation of these relationships to the overall continental area is in good agreement with the compilations of world-wide river data not only in terms of the global budgets but also in terms of the regional variability. Consequently, two global maps for river sediment fluxes are proposed in a grid-point scale: one map shows global sediment yields on the continents, while the other map shows the local inputs of the river sediments into the oceans. These maps represent, however, natural fluxes and do not account for sediment retetion due to damming of many rivers. In a recent study, Vörösmarty and others (1997) estimated that this effect may have reduced the global riverine sediment discharge to the oceans by about 16 percent.

DATA AND METHODS

River basins and literature data–Figure 1 shows the global distribution of the 60 river basins considered in this study. The river names, the average climates of the basins (see below), and the basin areas (A) are listed in table 1. The latter have been calculated in a 0.5° × 0.5° longitude/latitude grid point resolution using the digitized contour lines of the basins (Pinet and Souriau, 1988; Ludwig, Probst, and Kempe, 1996). Also the endoreic parts of the continents and the continental divides with respect to the different oceans have been digitized. The calculated basin areas compare well with other estimates cited in the literature. Discrepancies arise only for a few river basins that border to very dry regions, where it is difficult to define the basin limits (for example, the Nile or the Niger basins). Together, the 60 drainage basins cover about 50 percent of the total exoreic continental area, and they are representative of the major climates on Earth (Ludwig, Probst, and Kempe, 1996).

Table 2 lists the estimated runoff intensities (Q) and sediment yields (sediment fluxes divided by basin area–in the following abbreviated as sF_{TSS}) from literature sources for these rivers. With very few exceptions, sF_{TSS} values were taken from the recently published Global River Index (GLORI) database (Milliman, Rutkowski, and Meybeck, 1995), but all values refer to the discharge and basin size values used in this study. This means that we calculated mean annual sediment concentrations by taking the sediment fluxes and the discharge values given in the GLORI database, then multiplied these concentrations by the literature discharge estimates of table 2 (discharge = A × Q), and finally divided the resulting sediment fluxes by the basin areas calculated in this study. In by far most of the cases, however, this does not change the values much. Note that we always selected the values before damming of the rivers when this information was available. For some rivers, today's sediment fluxes can be considerably lower. A striking example for this is the Nile River, which now discharges almost no sediments into the Mediterranean Sea. One has also to mention that for most of the rivers, bedload transport has not been measured. On average, bedload transport may account for an additional flux of about 10 percent of the suspended matter flux (Milliman and Meade, 1983).

The values in table 2 are best estimates, and the numerous problems related to the determination of average sediment yields for river basins must be kept in mind when considering such a data compilation. Because of the temporal sediment storage capacity in river basins, a regular sampling for especially long time periods is needed to obtain reliable average values, and a high frequency of sampling is particularly important during flood periods. Naturally not all the values in table 2 could have been determined under these optimal conditions. Note, for example, that Meade and Parker (1985) reported from the investigation of rivers of the United States that in some cases, more than half the sediment load for the year is likely to be transported in only 5 or 10 days within any individual year. Also Probst and Bazerbachi (1986) found for the Garonne River in France that 50 percent of the sediment flux measured during a seasonal cycle was discharged within 17 days, with again about half of it within one single day. Especially in arid and semi-arid regions, where water discharge varies markedly both between years and within years, it is of great importance to have detailed and long term records. The flashiness of water discharges often observed in these regions makes it difficult to obtain observations at the gauging station at rising stages. Especially therefore data from semi-arid areas might be less reliable than data from other climates, unless data are automatically recorded (Jansson, 1988).

Environmental characterization of the river basins.–The above basin contours were used to extract the climatic, biological, morphological, and lithological characteristics of the investigated river basins from a great number of global data sets, thus allowing a complete environmental characterization of the basins. The parameters considered and the corresponding data sets we used are listed in table 3. For each basin and each parameter, one area-weighted mean value was calculated. One problem with such a proceeding is the huge difference in size between the investigated river basins. For some of the large basins, the climatic variability within the basin can be great (Ludwig, Probst, and Kempe, 1996), making an average basin value not always meaningful. Nevertheless, previous studies often proposed basin area itself to be an important controlling factor for river sediment yields (Milliman and Syvitski, 1992), and for this reason we think that it is important to include a broad range of basin sizes in a study like ours rather than to select only river basins of more or less the same size. Note that all calculations were made in a 0.5° × 0.5° longitude/latitude grid point resolution. As the original resolution of the considered data sets is different (table 3), we either extrapolated or interpolated the data linearly to this resolution.

Many of the global environmental data sets we used are freely available for scientific purposes. The data sets for Q and APPT have been created at our institute by digitizing and rasterizing (Ludwig and others, in press) the maps of the UNESCO Atlas of World Water Balance published by Korzoun and others (1977). A comparison of the Q values resulting from the digitized data set with the values on table 2 for the 60 rivers

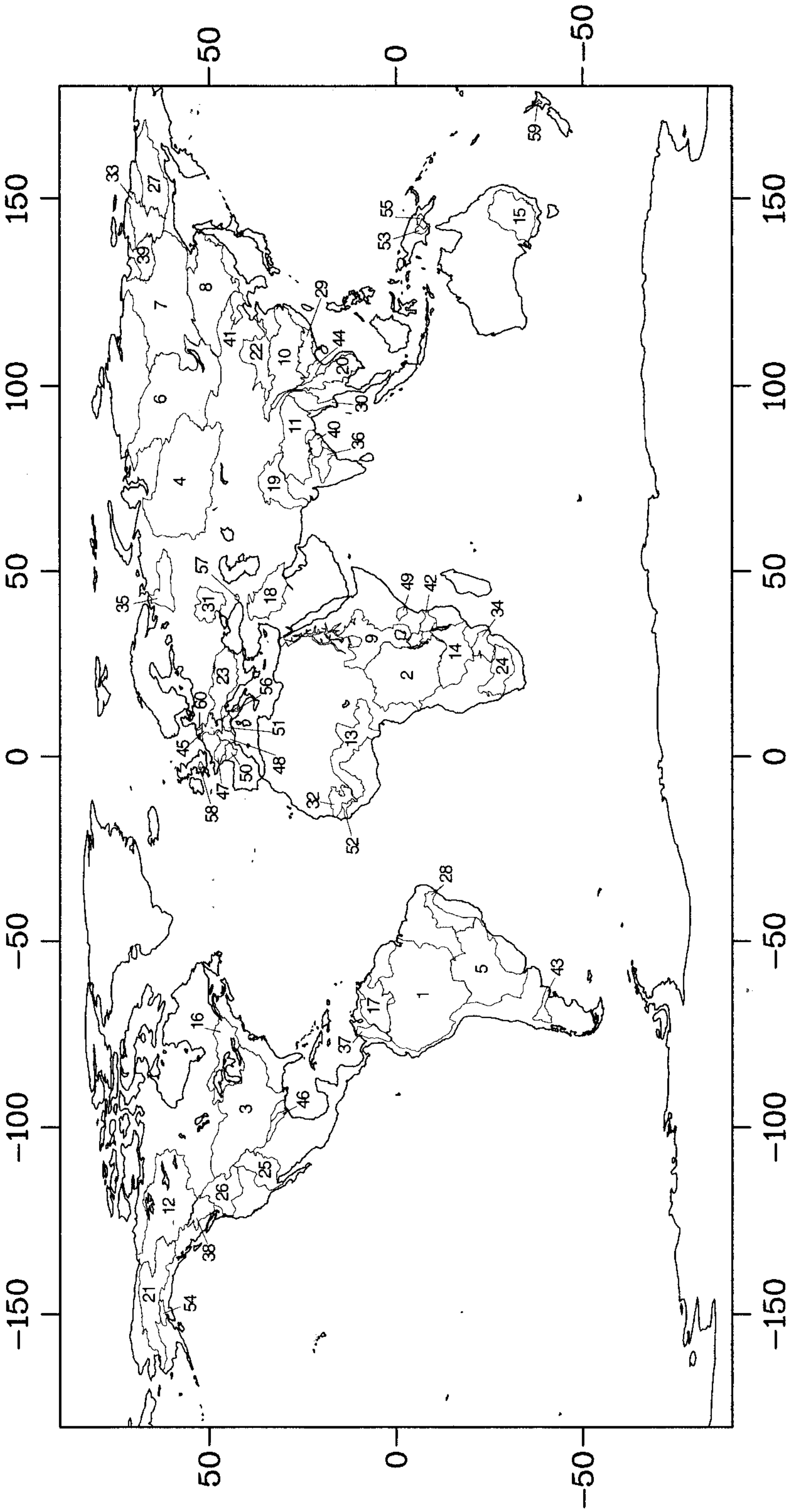

Fig. 1. World-wide distribution of the river basins investigated in this study. The river names corresponding to the numbers are listed in table 1.

investigated in this study revealed that the UNESCO maps are a realistic representation of average runoff intensity on the continents. Because the UNESCO precipitation maps give only mean annual values, we derived mean monthly precipitation totals by applying the monthly percentages of annual precipitation resulting from the monthly precipitation data sets of Legates and Willmott (1992) to the digitized and gridded UNESCO precipitation data set.

TABLE 1

Digitized river basins, their basin areas, and their average climates

River Basin	Basin #	Area, 10^6 km^2	CI [*]	River Basin	Basin #	Area, 10^6 km^2	CI [*]	River Basin	Basin #	Area, 10^6 km^2	CI [*]
Amazon	1	5.903	(8)	Yukon	21	0.843	(5)	Liao He	41	0.188	(7)
Zaire	2	3.704	(8)	Huanghe	22	0.823	(4)	Rufiji	42	0.180	(6)
Mississippi	3	3.246	(7)	Danube	23	0.773	(7)	Rio Negro (Argentine)	43	0.175	(4)
Ob	4	3.109	(5)	Orange	24	0.716	(6)	Hungho	44	0.159	(8)
Paraná	5	2.868	(8)	Colorado	25	0.708	(4)	Rhine	45	0.156	(7)
Yenisei	6	2.567	(5)	Columbia	26	0.664	(7)	Brazos	46	0.127	(6)
Lena	7	2.465	(5)	Kolyma	27	0.659	(5)	Loire	47	0.107	(7)
Amur	8	1.926	(7)	Sao Francisco	28	0.621	(6)	Rhône	48	0.097	(7)
Nile	9	1.874	(6)	Si Kiang	29	0.464	(8)	Tana	49	0.089	(6)
Changjiang	10	1.822	(7)	Irrawaddy	30	0.419	(8)	Garonne [**]	50	0.079	(7)
Ganges/Brahmaputra	11	1.656	(8)	Don	31	0.413	(7)	Po	51	0.067	(7)
Mackenzie	12	1.615	(5)	Senegal	32	0.369	(6)	Gambia	52	0.063	(6)
Niger	13	1.540	(6)	Indagirka	33	0.358	(5)	Fly	53	0.058	(8)
Zambesi	14	1.413	(6)	Limpopo	34	0.344	(6)	Susitna	54	0.057	(5)
Murray	15	1.131	(6)	North Dvina	35	0.329	(5)	Purari	55	0.040	(8)
St. Lawrence	16	1.114	(7)	Godavari	36	0.311	(6)	Tiber	56	0.016	(7)
Orinoco	17	1.026	(8)	Magdalena	37	0.285	(8)	Rioni	57	0.016	(7)
Tigris/Euphrates	18	0.927	(6)	Fraser	38	0.248	(7)	Severn	58	0.013	(7)
Indus	19	0.912	(6)	Yana	39	0.243	(5)	Waikato	59	0.012	(7)
Mekong	20	0.864	(8)	Mahandi	40	0.190	(6)	Ems	60	0.009	(7)

* CI is a climatic index characterizing the average climate of the entire river basin–see text: (4) temperate dry; (5) tundra and taiga; (6) tropical dry; (7) temperate wet; (8) tropical wet.
** Includes Dordogne.

TABLE 2

Drainage intensity and sediment yields for the rivers of table 1

River Basin	Runoff, mm	sF_{TSS}, t km^{-2} yr^{-1}	River Basin	Runoff, mm	sF_{TSS}, t km^{-2} yr^{-1}	River Basin	Runoff, mm	sF_{TSS}, t km^{-2} yr^{-1}
Amazon	1067 [*,#]	203 [#]	Yukon	249 [*,#]	71 [#]	Liao He	85 [#]	218 [#]
Zaire	373 [*]	13 [#]	Huanghe	72 [#]	1338 [#]	Rufiji	173 [#]	95 [#]
Mississippi	151 [*,#]	123 [#]	Danube	259 [*]	107 [#]	Rio Negro (Argentine)	165 [*]	72 [#]
Ob	134 [*]	5 [#]	Orange	15 [#]	124 [#]	Hungho	753 [#]	815 [#]
Paraná	189 [*]	32 [#]	Colorado	28 [#]	190 [#]	Rhine	462 [*]	16 [#]
Yenisei	229 [*]	5 [#]	Columbia	280 [*]	17 [#]	Brazos	54 [*]	122 [#]
Lena	216 [*]	8 [#]	Kolyma	213 [*]	26 [#]	Loire	246 [*]	71 [#]
Amur	178 [*]	29 [#]	Sao Francisco	193 [#]	10 [#]	Rhône	559 [*]	580 [#]
Nile	48 [#]	64 [#]	Si Kiang	646 [#]	149 [#]	Tana	81 [*,†]	1000 [@]
Changjiang	510 [#]	264 [#]	Irrawaddy	1026 [#]	620 [#]	Garonne	359 [‡]	77 [#]
Ganges/Brahmaputra	737 [#]	640 [#]	Don	66 [*]	16 [#]	Po	707 [*]	277 [#]
Mackenzie	167 [#]	51 [#]	Senegal	68 [*]	65 [#]	Gambia	133 [*,§]	5 [#]
Niger	130 [#]	26 [#]	Indagirka	163 [*]	35 [#]	Fly	1325 [#]	1377 [#]
Zambesi	71 [#]	34 [#]	Limpopo	15 [#]	96 [#]	Susitna	368 [$]	193 [#]
Murray	11 [#]	25 [#]	North Dvina	318 [*]	12 [#]	Purari	2137 [#]	2514 [#]
St. Lawrence	404 [#]	4 [#]	Godavari	323 [*]	548 [#]	Tiber	466 [#]	472 [#]
Orinoco	1072 [#]	205 [#]	Magdalena	843 [*]	773 [#]	Rioni	966 [*]	572 [#]
Tigris/Euphrates	117 [*]	255 [#]	Fraser	396 [*]	72 [#]	Severn	485 [*]	82 [#]
Indus	263 [#]	274 [#]	Yana	134 [*]	14 [#]	Waikato	1074 [*,#]	132 [#]
Mekong	544 [#]	185 [#]	Mahandi	495 [*]	451 [#]	Ems	404 [£]	27 [@]

Sources: *, Global Runoff Data Centre Koblenz, 1991; #, references are listed in Milliman, Rutkowski, and Meybeck, 1995; †, Charania, 1988; ‡, Probst, ms; §, Lesack, Hecky, and Melack, 1984; $, Meybeck, ms; £, Cadée, 1987; @, Milliman and Syvitski, 1992.

TABLE 3

Environmental parameters considered in this study

Parameter group	Environmental parameter	Abbreviation	Resolution	Source
hydroclimatic parameters	monthly and annual temperature mean (°C)	MT, AT	0.5° × 0.5°	Legates and Willmott, 1992
	monthly and annual precipitation total (mm)	MPPT, APPT	0.5° × 0.5°	this study; Korzoun ant others, 1977; Legates and Willmott, 1992
	mean annual runoff intensity (mm)	Q	0.5° × 0.5°	this study; Korzoun ant others, 1977
	seasonal precipitation variability (mm)	Four	0.5° × 0.5°	CORINE, 1992; Fournier, 1960
	Aridity Index	ArIn	0.5° × 0.5°	CORINE, 1992
biological parameters	biomass density (kg/m^2)	VegC	0.5° × 0.5°	Olson, Watts, and Allison, 1983; 1985
	netto primary production (kg/m^2)	NPP	0.5° × 0.5°	Olson, Watts, and Allison, 1983; 1985
	forest ratio (% of all vegetation types / 100)	ForR	0.5° × 0.5°	Olson, Watts, and Allison, 1983; 1985; Claussen and others, 1994
	oranic carbon content in the soils (kg/m^3)	SoilC	10' × 10'	USDA Soil Conservation Service
pedological parameters	average soil depth (cm)	SoilH	1° × 1°	Webb, Rosenzweig, and Levine, 1991
	average soil texture	SoilTI	1° × 1°	Webb, Rosenzweig, and Levine, 1991; CORINE, 1992
morphological parameters	modal basin elevation (m), maximum basin elevation (m)	Elev, ElevM	10' × 10'	FNOC, 1992
	local relief (m)	LR	10' × 10'	FNOC, 1992; Ahnert, 1970
	surface slope (radian)	Slope	5' × 5'	Moore and Mark, 1986
lithological parameters	chemical erodibility index of lithology	LithCI	1° × 1°	Amiotte Suchet, 1995
	mechanical erodibility index of lithology	LithMI	1° × 1°	Probst, 1992
anthropogenic parameters	mean population density (h/km^2)	PopD	2.5° × 2.5°	Ahamer and others, 1992
	percent of cultivated area (%)	CultA	0.5° × 0.5°	Olson, Watts, and Allison, 1983; 1985

Among the hydroclimatic parameters, two parameters were calculated accounting for seasonal variability. According to CORINE (1992), we quantified the seasonal variability of precipitation by calculating the sum of the square of mean monthly precipitation over mean annual precipitation for all 12 months of the year (see also Ludwig, Probst, and Kempe, 1996). This parameter was named Four because Fournier (1960) proposed a very similar index, although he only selected the ratio of the square of precipitation of the month with the greatest value over the annual precipitation total. Moreover, seasonal aridity was characterized as dimensionless parameter by taking the sum of two times the mean monthly temperature minus the monthly precipitation total for all months of the year where this value is positive (CORINE, 1992).

The average organic carbon content in the soils was determined on the basis of a global data set created at the Soil Conservation Service of the United States Department of Agriculture. As additional soil parameters, we included in this study the data sets of Webb, Rosenzweig, and Levine (1991) which contain information on the soil texture and the soil profile thickness in a spatial resolution of 1° × 1° longitude/latitude. However, spatial resolution is misleading here if one takes it as a measure for the spatial precision of the data. The data sets were created by extrapolating the selected soil profiles representing each soil type in the FAO soil maps over the continents, following the FAO soil map digitized by Zobler (1986). Local and regional variability, for example, of soil depth due to climatic and morphological variability is thus not taken into account here. We used this data set also to derive an index for soil erodibility based upon the average soil texture. The average soil composition of each grid element was plotted in a soil texture triangle (percent clay, percent silt, percent sand) and a three-point scale ranging from 1 (slightly erodible) to 3 (highly erodible) was assigned depending on the position of the grid element in the triangle. Also this assignment was made according to CORINE (1992).

Information on lithology was taken from two global data sets created at our institute during previous studies. One data set classifies the major rock types on the continents according to their resistance to mechanical erosion, assigning a numerical index (LithMI) to each rock type. LithMI ranges from 1 to 40 with 1 = plutonic and metamorphic rocks, 2 = volcanic rocks, 4 = consolidated sedimentary rocks, 10 = different rock types in folded zones, 32 = non-consolidated sedimentary rocks, and 40 = recent alluvials (Probst, 1992). A second global lithological map was developed to predict the consumption of atmospheric CO_2 by rock weathering (Amiotte-Suchet, 1995; Amiotte-Suchet and Probst, 1993a, b, 1995). This map allows us to assign a numerical index characterizing the resistance of each rock type to chemical erosion (LithCI).

Finally one must also mention that all climatic distinctions made in our study follow the simple climatic classification of Ludwig, Probst, and Kempe (1996). This classification is based on the repartition of a given site in the Holdridge Life Zone Triangle (Holdridge, 1947), depending on its average temperature and precipitation patterns only. On the whole, eight climate types are distinguished: (1) polar with ice; (2) polar without ice; (3) desert; (4) temperate dry; (5) tundra and taiga; (6) tropical dry; (7) temperate wet; (8) tropical wet. All river basins were classified according to the average temperature and precipitation characteristics of the entire basin. We consider to be dry all climate types that fall either into the tropical or temperate dry climate type, or that are desert. Consequently all other climate types are wet climate types. As far as we did our calculations on a grid point level, we applied the same classification to the individual grid points of the continents. Note that all regional and global budgets given in this study refer only to the exoreic and ice-free areas of the continents, which we calculated to be about 106×10^6 km^2 on the whole.

PREVIOUS MODELS FOR THE PREDICTION OF RIVER SEDIMENT FLUXES

The following sections review some of the different models proposed in the literature for the empirical prediction of river sediment yields. Table 4 gives an overview of these models. The literature review is interesting not only because it gives a state-of-the-art in the field of modelling but also because it mentions additional data, which could not be included in our study. All models predicting mechanical denudation rates estimated them from river sediment fluxes, so that the two terms can be considered as synonyms here, which is, due to possible uplift and subsidence of river basins, not the case in general. Whenever this was possible, we applied the proposed relationships to the data sets used in this study, and the resulting amounts of total sediments that should be discharged to the oceans according to the relationships were calculated to get an-order-of-magnitude estimate when the authors did not extrapolate their findings to the global scale. The calculated figures may then be compared with global and regional estimates for river sediment fluxes that were made based upon compilations of world-wide river data. Such compilations have been done, for example, by Holeman (1968) or by Milliman and Meade (1983), resulting in global fluxes of about 20 Gt (gigatons, 10^6 t) and 13.5 Gt (with an upper limit of 16 Gt) per year, respectively. In a more recent work based upon a greater number of river data especially for small basins, Milliman and Syvitski (1992) supposed that global F_{TSS} may be as great as 20 Gt/yr.

Relationships with precipitation.–Precipitation has been widely held to have a predominant influence on river sediment yields. Several non-linear relationships have been proposed linking the two parameters. Some are depicted in figure 2. Although there is little agreement in detail between these postulated relationships, certain common elements emerge. An initial peak of erosion is observed in semi-arid environments, and a progressive increase in denudation above a mean annual precipitation value of about 1000 mm occurs. The existence of such a two-maxima curve has been at least partly related to the role of vegetation. The presence of vegetation greatly reduces the

TABLE 4

Summary of the different models for sediment yield prediction discussed in the text

Study	Parameters used for sediment yield prediction *	Global (Regional) FTSS, Gt/yr	Remarks
Langbein and Schumm, 1958	APPT	(10.8) $	Hand-fitted relationship. The given sediment flux corresponds only to about 42% of global *APPT* (250-1250 mm range).
Douglas, 1967	APPT	(11.5) $	Hand-fitted relationship. The given sediment flux corresponds only to about 42% of global *APPT* (250-1250 mm range).
Wilson, 1973	APPT	(19.3) $	Hand-fitted relationship. The given sediment flux corresponds only to about 42% of global *APPT* (250-1250 mm range).
Ohmori, 1983	APPT	56.6 $	As above, but the relationship was also extrapolated to the remainder 58% of global *APPT* (incl. > 1250 mm range) - see text
Fournier, 1960	Four, Relief	64.0	Sediment yields were correlated with a seasonality index for precipitation. Different relationships for different relief types.
Pinet and Souriau, 1988	Elev, Orogeny Type	16.2 $	2 linear relationships with elevation depending on the orogeny type. Important sedimentation (17.6 $ Gt/yr) in young orogenies.
Ahnert, 1970	LR	9.3 $	Linear relationship with local relief (which is the difference between maximal and minimal elevation in a given sector).
Jansen and Painter, 1974	Q, A, Elev, Slope AT, LithMI #, VegI §	26.7	Multiple correlation models depending on the climate type to which the drainage basins belong. Variable basin sizes.
Probst, 1992 - model I	Slope, Q, APPT, VegI §	22.9	Multiple correlation model on the basis of data from large river basins. Best model including 4 variables.
Probst, 1992 - model II	Slope, LithMI, APPT Q, VegI	21.7	Multiple correlation model on the basis of data from large river basins. Best model including 5 variables.

* For parameter abbreviations, see table 3.
\# Note that the index Jansen and Painter (1974) used is different compared to the one used in this study–see text.
§ VegI is an index characterizing the soil protection capacity of vegetation–see text.
$ Values calculated in this study.

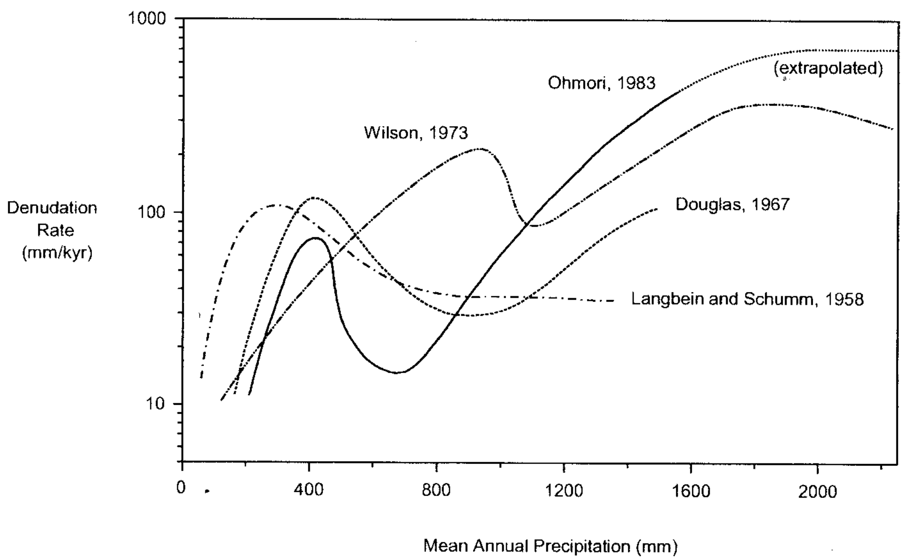

Fig. 2. Proposed relationships between denudation rate and mean annual precipitation (figure from Summerfield, 1991).

erodibility of surface materials, and the abrupt retardation of mechanical denudation rates above the precipitation value at the first maximum was attributed to a marked increase of vegetation cover (Langbein and Schumm, 1958). With increasing precipitation, the maximum protective effect of vegetation may be reached, and beyond a certain threshold value, increasing precipitation (and thus also runoff) tends to increase the rates of mechanical erosion.

Langbein and Schumm (1958) proposed a mathematical formula for their relationship, but normally the curves in figure 2 were obtained through a by-hand-fitting of data points, often with a great scattering of the data around the curve (as noted, for example, by Wilson, 1973). Because all curves cover the APPT-range of 250 to 1250 mm, we fitted spline interpolations to them in this range and then calculated the corresponding sediment fluxes by applying the relationships to the global precipitation data set used in this study. According to Summerfield (1991), a mean rock density of 2700 kg/m^3 was taken for the conversion of denudation rates to weight units. This leads to sediment fluxes between 8.8 and 19.3 Gt/yr (table 4). Note that the 250 to 1250 mm precipitation range contributes about 42 percent of total precipitation falling on the continents.

For the remainder 58 percent of precipitation, an estimation of the corresponding F_{TSS} values is, of course, speculative. Taking only the relationship of Ohmori (1983), which is based on the largest set of observations (as mentioned in Summerfield, 1991), an extrapolation of the curve up to 2000 mm (see fig. 2) yields an additional sediment flux of 23.4 Gt/yr for the 1250 to 2000 mm precipitation range, corresponding to about 27 percent of total precipitation. Assuming then that the curve does not increase further above 2000 mm and that the denudation rate remains constant, yields again a sediment plus of about 24.4 Gt/yr for the rest of total continental precipitation (the <250 mm precipitation range can be neglected here). The total amount of sediment that should be discharged to the oceans according to the relationship of Ohmori would therefore sum up to a value of about 57 Gt/yr.

It must be stated that the above made extrapolations are naturally debatable, and the calculated sediment fluxes should only be considered as order-of-magnitude estimates. But the extrapolations indicate that the proposed sediment yield-precipitation relationships tend to produce much higher global sediment fluxes compared to the world-wide river data compilations (see above), at least as far as they include a second maximum in the range above 1000 mm (all curves except the one of Langbein and Schumm, 1958).

In this context, it is also interesting to mention the approach of Fournier (1960) to predict sediment yields, even if he established individual regressions for different ranges of relief, and this approach can thus be considered as a combined parameter model (combined parameter models are discussed below). He selected the month of the year where precipitation is greatest and proposed river sediment yields to be correlated with the ratio of the square of this monthly precipitation over the mean annual precipitation. Fournier's approach underlines the importance of a strong seasonality of precipitation for sediment fluxes, but his index is naturally also highly correlated with total precipitation. When he extrapolated his models to the total continental area, he calculated an overall sediment flux of more than 64 Gt/yr, which is also far above from what is found with the world-wide river data compilations.

Relationships with climate.–Because precipitation is a central element of climate, the relationships discussed above can be considered a special case of sediment yield-climate relationships. Climate, however, is characterized by a multitude of additional parameters and factors, of which temperature and seasonal variability are the most important.

One of the most extensive studies investigating the relationships between sediment yields and climate is the one of Jansson (Jansson, 1982, 1988). She used a climatic classification modified from Köppen's classification (Köppen, 1936) which is different from the classification applied in this study because the Köppen classification also distinguishes seasonal features such as the occurrence of dry or wet periods or monsoon rains. Jansson reported very high sediment yields in the non-seasonal tropical climate but relative low values in the tropical climate with a dry season (although a great scatter occurred in nearly all climate classes that were studied). In contrast, the warm temperate climates with a dry season were found to exhibit rather high values but not the warm temperate climates without a dry period. Boreal climates were found to have low values, except for climates being boreal as a consequence of altitude rather than of latitude, where sediment yields were usually greater. Jansson did not try to extrapolate her findings to the global scale to reach an estimate for the total sediment flux to the oceans, probably because of the great amount of scatter in the data. But one may state here that her investigations confirm to some extent the trends emerging in the above discussed sediment yield-precipitation relationships: great sediment yields were found both in dry regions (which may correspond to the first maxima in the F_{TSS}-APPT curves of fig. 2) and in very humid tropical regions (which may correspond to the second maxima). However, the great scattering in her data indicates that climate alone is probably not a useful criterion to predict river sediment yields.

Relationships with basin elevation and morphology.–Many studies have pointed out the great influence of basin elevation and morphology on river sediment fluxes, but only a few of them proposed mathematical relationships. Among these studies are the ones of Pinet and Souriau (1988) and the one of Ahnert (1970). The former authors found river sediment fluxes to be linearly correlated with mean basin elevation, whereas the latter author proposed a linear relationship with local relief, which is the difference between maximal and minimal elevation in a given sector. For the study of Ahnert this is not completely true because he considered both chemical and mechanical denudation rates, even if it can be supposed that by far the larger parts in the values he used should reflect sediment transport.

Looking mainly at river sediment yields of large world rivers, Pinet and Souriau (1988) proposed the following two equations to describe mechanical denudation globally:

$$\mathrm{Ds} = 419 \times 10^{-6}\,\mathrm{Elev} - 0.245 \tag{1}$$

$$\mathrm{Ds} = 61 \times 10^{-6}\,\mathrm{Elev} \tag{2}$$

Ds is the mean denudation rate in m/kyr, and Elev the mean basin elevation in m. Eq(1) is valid for mechanical denudation taking place in regions related to orogenies younger than 250 my, while eq (2) is related to orogenies older than 250 my. The considerable intercept in eq (1) was attributed by the authors to continental sedimentation in the basins associated with young orogenies.

An assignment of the crust ages of the continents is needed to apply these equations to the total continental area on the basis of the elevation data used in this study. For a first-order-approximation, we followed the distribution given by Burchfiel (1983) and classified all grid points of the continents according to whether they belong to regions older than 250 my or to regions younger than 250 my (fig. 3). Pinet and Souriau selected this limit to separate young and old orogenies. Then eqs (1) and (2) were applied to the corresponding regions, resulting in a total sediment flux to the oceans of about 16.2 Gt/yr. About 5.2 Gt/yr originate from old continental crust (73 percent of the total area), while 11 Gt/yr come from young continental crust (27 percent of the total area). In the latter regions, however, more than 17.6 Gt/yr should be stored by continental sedimentation according to the negative intercept in eq (1). This is more than the total amount of sediments exported to the oceans. Note that for the calculations, only a mean rock

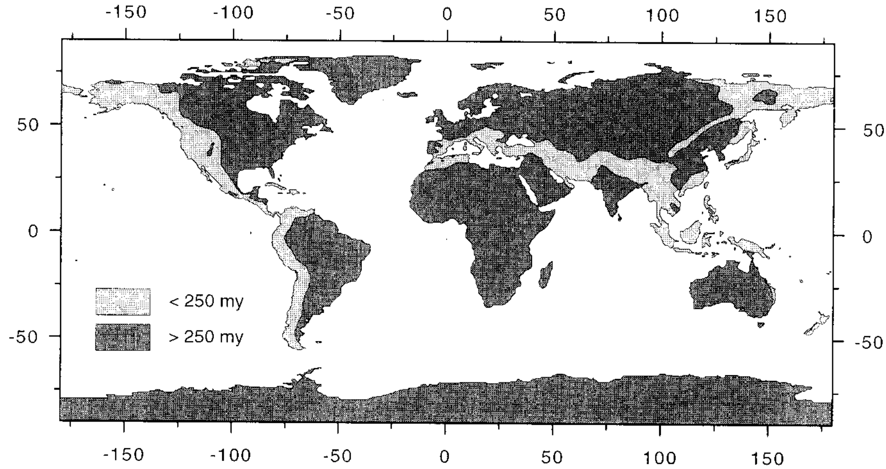

Fig. 3. Distribution of continental crust younger than 250 my (modified from Burchfiel, 1983).

density of 2500 kg/m^3 was taken this time for the conversion of denudation rates to sediment fluxes according to the value taken by Pinet and Souriau.

The global sediment flux estimate derived is in better agreement with the estimates from the world-wide river data compilations than is the case for the sediment yield-precipitation relationships discussed above. But correlating river sediment yields with elevation can hardly be justified on the basis of a causal relationship between both parameters, because the flux of sediment at a specific location should be a function of the gradient at that point, irrespective of its elevation above mean sealevel. This has also been pointed out by Summerfield and Hulton (1994) who did a compilation of sediment yield data for major world rivers together with a detailed characterization of the morphology of the basins. They reported that, at first sight, the idea that mechanical denudation rates vary as a function of mean elevation would appear to be supported by their data, but they show at the same time that basin elevation is also strongly correlated with other topographic factors, which show even greater correlation with sediment yields, such as, for example, basin slope.

For this reason, it is interesting to look at the study of Ahnert (1970), because he related denudation rates to local relief instead of mean elevation. He proposed the following equation to be the best model for denudation rates:

$$Ds = 153.5 \times 10^{-6}\,LR - 10.88 \times 10^{-3} \tag{3}$$

Ds is again the mean denudation rate in m/kyr, and LR the local relief in m. In his work, Ahnert showed also that local relief is strongly correlated with slope, but it is difficult to apply the relationship he found to the slope data used in our study. In order to apply eq (3) to the global scale, we derived therefore from the elevation data used in this study a global LR data set by calculating the difference between maximal and minimal elevation in a 10' × 10' longitude/latitude resolution. This is comparable with the approach of Ahnert. He derived local relief by taking the values from topographical maps within sectors of 400 km^2 each, while a 10' × 10' grid element at the equator comprises an area of about 340 km.^{2} This is not greatly different but nevertheless finer than the resolution selected by Ahnert, in as much as the size of one sector naturally decreases when going to higher latitudes. With the data set thus created, a global sediment flux to the oceans of about 9.3 Gt/yr is found with eq (3) (again a mean rock density of 2500 kg/m^3 was taken for the conversion of denudation rates to sediment fluxes according to Ahnert). Given the fact that a finer resolution tends to produce greater LR values than a coarse resolution, this is an upper limit.

The global scale extrapolations of the relationships presented here are naturally dependent on the question of to what extent the data used to establish the relationship are representative at the global scale. If this is the case, however, one may conclude that a simple coupling of sediment yields to morphological parameters requires either a very different behavior of mechanical denudation in the young orogenic belts of the continents (according to eqs 1 and 2 about 10 times greater than in the older parts of the continents), or it leads to erosion rates that tend to be somewhat too low compared to the estimates derived from the world-wide river data compilations. This is true in as much as the global sediment fluxes calculated with the morphological parameter models should be maximum values because they include also some desert parts of the continents, where nearly no water runs off.

Combined parameter models.–Because of indications both for climatic and morphological controls, one may finally look at combined parameter models proposed to predict river sediment yields globally. Jansen and Painter (1974) investigated sediment yields for 79 river basins (basin area > 5000 km^2) together with 8 potential controlling factors: runoff intensity (Q, mm), basin area (A, km^2), mean elevation (Elev, m), Slope (relief length ratio = equivalent to main channel slope, m/km), annual precipitation total (APPT, mm), mean annual temperature (AT, °C), an index characterizing the soil protection capacity of vegetation (VegI, deserts = 1 to forest = 4), and an index characterizing the softness of lithology (LithMI, 2 = hardly erodible to 6 = easily erodible). For all rivers together, they found the following model to be the best model to predict sediment yields globally (the unit of sF_{TSS} is t km^{-2} yr^{-1}):

$$\log sF_{TSS} = 0.100 \log Q - 0.314 \log A + 0.750 \log Elev + 1.104 \log Slope + 0.368 \log AT + 0.786 \log LithMI - 2.324\, VegI - 2.032 \quad (4)$$

Jansen and Painter (1974) also grouped the basins according to a fourfold climatic classification and repeated the statistics within each of the groups. The trends in the resulting equations remained similar to those of eq (4). Sediment fluxes increased with increasing runoff, altitude, relief, precipitation, temperature, and rock softness, and they decreased with increasing basin area and increasing vegetation protection, even if some prominent exceptions occurred. Based on their different climatic models, they extrapolated the global sediment flux to be 26.7 Gt/yr.

In a similar study, Probst (1992) proposed on the basis of data for large river basins two multiple regression models to predict sediment fluxes with 4 and 5 parameters, respectively:

$$\ln sF_{TSS} = 0.9655 \ln Slope + 0.0023\, Q + 0.5692 \ln APPT - 0.8660\, VegI + 1.561 \quad (5)$$

$$\ln sF_{TSS} = 1.028 \ln Slope + 0.0365\, LithMI + 0.6932 \ln APPT + 0.0016\, Q - 0.7516\, VegI - 72.3 \times 10^{-3} \quad (6)$$

Variables and units are the same as in eq (4), but this time Slope was calculated in the same way as in this study (but the unit is percent), VegI ranges from zero to 6 (desert to forest), and LithMI is the same index used in this study (see above). When he applied eqs (5) and (6) to the corresponding parameter averages calculated for 10° latitudinal bands, he found total sediment fluxes of 22.9 and 21.7 Gt/yr, respectively.

As may be expected, the global sediment flux estimates derived by the combined parameter models lie between the estimates obtained from the regression models uniquely based on precipitation data and the models uniquely based on morphological data. However, one has to mention here that the above described combined parameter models are very scale-dependent. The flux estimates have been established on the basis of large scale averages, and it is doubtful whether similar results would be obtained if equations were applied to finer spatial scales because many parameters enter the equations in an exponential way.

A NEW APPROACH FOR THE MODELLING OF THE CLIMATIC, MORPHOLOGICAL AND LITHOLOGICAL CONTROL OF RIVER SEDIMENT YIELDS

We have seen on the previous pages that literature models for the prediction of river sediment yields can be highly variable with respect to the retained controlling parameters, as well as with respect to the total sediment fluxes they predict. This makes the applicability of these models for prediction purposes highly questionable. We therefore investigated what the major controlling factors for river sediment yields are on the basis of the data used in this study, and whether it is possible to use them for prediction of sediment yields not only on global but also on regional scales.

Identification of the controlling parameters.–Figure 4 shows a graphically presented correlation matrix between sediment yield (sF_{TSS}) and most of the environmental parameters determined for the 60 river basins investigated in this study. The environmental parameters are listed in table 5. One can see that runoff (Q) has the strongest correlation with sF_{TSS} among all parameters considered. The next strongest correlation with sF_{TSS} includes total annual precipitation (APPT) and seasonal precipitation variability (Four). VegC, LithMI, and Slope correlate much less well. Correlation of certain variables with sF_{TSS} does not necessarily indicate a causal relationship because multicollinearity exists between various parameters. Strong multicollinearity exists especially

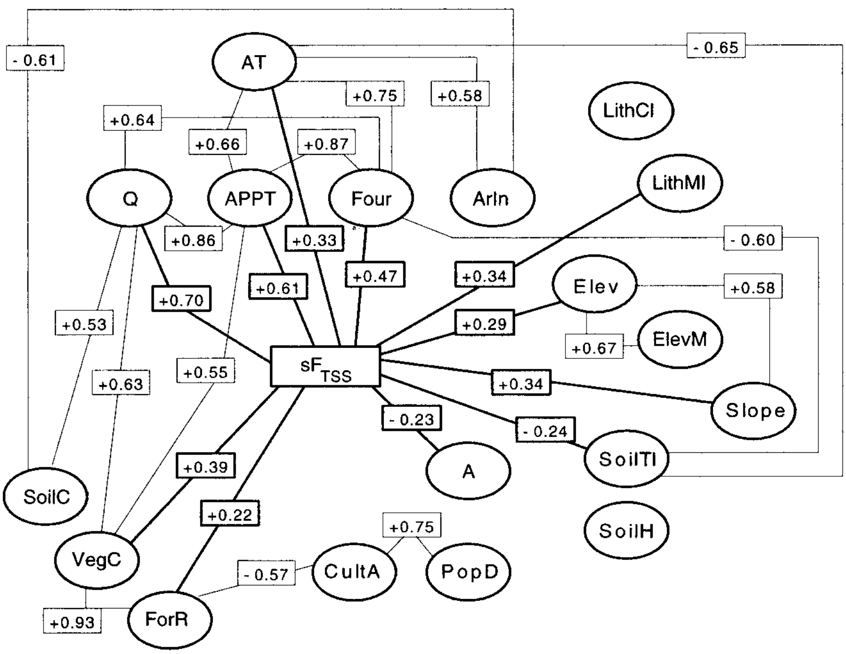

Fig. 4. Correlation between sediment yields (sF_{TSS}) and different environmental parameters (bold lines; only regressions significant with $P < 0.1$ are depicted) for the 60 river basins of table 1, as well as correlation between these environmental parameters (fine lines; only regressions with correlation coefficients < -0.5 and $> +0.5$ are depicted). Four parameter abbreviations, see table 3 (p. 270).

TABLE 5

Average environmental characteristics for the rivers of table 1

River	AT, °C	APPT, mm	Four. mm	VegC, kg/m²	NPP, kg/m²	ForR, %	SoilC, kg/m³	Elev, m	Slope, radian	SoilH, cm	LithMI,	CultA, %	PopD, h/km²
Amazon	24.1	2228	235	11.7	0.669	68	11.2	455	0.0434	226	22.4	0.9	2
Zaire	23.6	1541	173	8.4	0.603	59	10.7	775	0.0370	310	9.6	3.5	15
Mississippi	11.0	895	86	3.1	0.487	19	12.3	646	0.0497	214	16.1	38.4	27
Ob	-0.4	524	57	4.4	0.406	30	29.2	305	0.0345	216	26.0	12.6	7
Paraná	21.2	1223	135	3.3	0.424	19	11.3	503	0.0443	228	19.8	15.1	14
Yenisei	-4.6	555	72	7.6	0.377	55	15.4	769	0.0855	93	9.6	2.7	2
Lena	-8.5	445	59	6.0	0.318	50	13.6	608	0.0857	49	7.7	1.6	1
Amur	-1.0	591	97	6.9	0.472	51	23.6	571	0.0699	137	11.6	7.5	29
Nile	24.2	816	111	2.8	0.454	23	10.8	892	0.0577	221	5.2	17.8	28
Changjiang	14.5	1164	143	5.3	0.457	31	12.8	1527	0.1321	196	12.3	25.5	205
Ganges/Brahm.	21.8	1516	269	3.7	0.477	22	12.1	1406	0.1353	153	20.8	37.9	193
Mackenzie	-3.5	463	46	8.2	0.375	60	34.9	634	0.0964	184	8.5	0.2	1
Niger	27.1	1079	180	3.1	0.467	30	6.1	377	0.0303	294	11.9	9.5	43
Zambesi	21.3	930	163	5.4	0.522	45	7.4	994	0.0450	249	14.4	12.0	21
Murray	17.8	466	42	4.0	0.444	31	8.4	272	0.0337	161	15.8	20.5	6
St. Lawrence	5.5	1058	92	5.8	0.519	43	14.7	274	0.0407	210	4.6	24.1	25
Orinoco	25.6	2124	225	8.2	0.592	51	12.4	347	0.0549	228	23.8	2.1	13
Tigris/Euphrates	20.3	287	42	1.6	0.332	5	3.6	625	0.0933	200	15.9	23.2	46
Indus	19.8	593	98	2.2	0.331	11	5.3	1671	0.1476	92	20.9	19.6	121
Mekong	23.2	2225	322	8.1	0.609	55	11.1	854	0.0858	210	13.5	16.2	59
Yukon	-4.2	502	55	4.2	0.251	35	19.7	748	0.1468	219	12.5	0.0	<1
Huanghe	8.7	501	78	2.0	0.367	8	11.0	1839	0.1196	179	22.5	29.8	157
Danube	9.4	889	81	4.1	0.577	28	15.5	514	0.1250	154	21.7	56.0	125
Orange	18.0	427	54	1.4	0.318	6	3.8	1256	0.0484	160	13.2	5.3	9
Colorado	13.3	429	44	4.2	0.322	24	4.3	1505	0.1718	176	11.2	2.1	6
Columbia	7.5	796	79	8.5	0.442	43	8.1	1336	0.2197	232	4.9	10.1	16
Kolyma	-10.2	415	46	3.7	0.246	28	10.4	590	0.1195	24	12.0	0.0	<1
Sao Francisco	23.1	1132	156	4.0	0.468	32	6.5	627	0.0449	261	6.0	5.7	45
Si Kiang	20.7	1595	201	2.8	0.463	11	10.4	598	0.0805	198	9.6	30.4	199
Irrawaddy	23.1	1936	298	8.5	0.631	56	10.9	745	0.1477	242	22.9	15.3	39
Don	6.8	583	53	1.2	0.500	2	11.6	138	0.0147	234	22.0	73.2	37
Senegal	28.3	674	147	2.7	0.466	29	3.2	223	0.0216	133	14.3	10.5	6
Indagirka	-14.5	342	44	3.6	0.241	27	10.7	738	0.1261	37	14.8	0.0	<1
Limpopo	20.2	738	101	3.2	0.434	30	6.5	795	0.0498	189	10.2	14.0	11
Northern Dvina	0.6	738	73	8.1	0.466	68	24.9	127	0.0141	342	19.3	0.5	1
Godavari	26.6	1149	216	3.8	0.568	30	11.6	399	0.0433	154	4.8	44.2	260
Magdalena	23.4	2225	219	5.3	0.548	38	11.0	1224	0.2527	194	16.5	7.5	21
Fraser	5.5	953	90	14.2	0.585	81	9.2	1173	0.2555	178	7.4	2.4	1
Yana	-14.6	310	48	3.5	0.235	25	10.1	746	0.1290	30	11.6	0.0	<1
Mahandi	26.5	1563	295	4.7	0.590	29	8.3	318	0.0497	147	7.0	50.0	412
Liao He	6.3	635	111	3.6	0.503	23	17.3	488	0.0698	166	16.3	45.5	203
Rufiji	21.8	1061	168	4.2	0.496	35	9.3	864	0.0963	248	10.0	12.3	52
Rio Negro (Arg.)	12.5	370	40	1.7	0.264	9	3.9	697	0.0773	178	9.3	4.2	14
Hungho	21.1	1843	263	7.7	0.605	56	10.7	897	0.1315	306	11.0	13.3	133
Rhine	8.1	1215	105	5.3	0.539	33	17.8	579	0.1372	189	18.3	44.6	190
Brazos	18.1	795	74	2.5	0.471	15	12.3	438	0.0255	256	18.2	24.7	24
Loire	10.9	969	83	3.3	0.569	23	15.0	306	0.0667	161	8.7	50.8	135
Rhône	10.2	1131	99	3.7	0.513	30	14.4	805	0.2443	127	8.8	33.2	103
Tana	24.5	525	77	4.7	0.473	41	6.1	403	0.0383	316	1.1	11.1	31
Garonne	11.5	1079	93	4.7	0.540	31	13.7	483	0.1211	139	5.8	36.0	71
Po	11.8	1049	95	3.5	0.492	24	14.5	501	0.1903	161	21.2	53.1	167
Gambia	26.6	1067	214	2.3	0.501	22	5.5	223	0.0336	172	15.5	23.7	9
Fly	26.2	3455	327	12.6	0.512	60	11.6	198	0.0714	234	32.0	0.0	9
Susitna	-0.5	711	76	4.1	0.226	29	17.4	790	0.1899	186	18.3	0.0	1
Purari	22.5	3402	294	15.1	0.706	75	18.4	1176	0.2276	177	20.4	0.0	22
Tiber	13.1	1153	108	4.4	0.533	39	17.7	437	0.2542	111	9.5	0.0	62
Rioni	8.3	1410	121	2.0	0.486	9	10.0	1421	0.3093	23	13.2	28.3	26
Severn	9.4	981	84	1.0	0.600	0	16.7	153	0.0584	165	9.3	100.0	389
Waikato	11.7	1837	157	7.4	0.590	59	15.9	433	0.0922	140	10.0	0.0	3
Ems	8.6	1043	89	1.6	0.580	6	27.3	113	0.0391	213	24.1	80.0	169

For parameter abbreviations, see table 3 (p. 270).

between the different hydroclimatic variables as well as between the hydroclimatic and the biological variables. The good correlation between Q and VegC may explain, for example, why there is a positive correlation between VegC and sF_{TSS}, whereas one should expect an inverse relationship between both parameters because of the protection of the soils against mechanical erosion by a dense plant cover (as discussed above). Note that no multicorrelation occurs between the hydroclimatic and the geomorphological parameters.

Linear multiple correlation statistics do not yield a significant increase in the correlation between sF_{TSS} and the parameters shown in figure 4, when compared to the correlation between sF_{TSS} and Q. However, some improvement is obtained by using the product of certain parameters. The following equation gives the best model to describe the sediment fluxes globally:

$$sF_{TSS} = 0.020\,(Q \times \text{Slope} \times \text{Four})$$
$$n = 58, \quad r = 0.91, \quad P < 0.0001 \tag{7}$$

The units are t km^{-2} yr^{-1} for sF_{TSS}, mm for Q and Four, and radian for Slope; r is the correlation coefficient, P is the significance level, and n is the number of river basins considered in the equation. Note that the product of Q, Slope, and Four (in the following also P3) was calculated by forming the product of all grid points in the basins and not as the product of the basin averages. Including our index characterizing the abundant basin lithology with respect to mechanical erosion (LithMI) in the parameter product can still increase the correlation coefficient ($r = 0.93$), but this leads to a significant positive intercept ($P < 0.1$) in the regression, which makes the model less suitable for sediment yield predictions.

In eq (7), we omitted the Huanghe River in China and the Tana River in Kenya from the regression. Both rivers have by far the greatest specific sediment fluxes of all rivers included in this study. The extreme sediment yield found for the Huanghe River is related to one of its tributaries, the Huangfuchuan River. This tributary drains a highly erodible loess-covered terrain, leading to a specific sediment export of more that 50000 t $km^{-2}yr^{-1}$ (Summerfield, 1991). Such local particularities cannot be taken into account in a study such as this one. It has been show that it is probably the interaction of the great erodibility of the abundant loess together with its extensive agricultural use that leads to the extremely great sediment fluxes of the Huanghe River (Milliman and others, 1987). Also the high sediment load of the Tana River seems to be related to a particular, very erodible region in the basin (Charania, 1988), but the literature value for this river may also to be less reliable.

On the basis of our global Q, Slope, and Four data sets, eq (7) results in an average global sediment yield of 139.4 t $km^{-2}yr^{-1}$ when applied to a total continental area (exoreic and ice-free). The total sediment flux is 14.80 Gt/yr. This value is in good agreement with the above mentioned world-wide river data compilations.

Climatic particularities.–Forming the product of parameters can lead to large differences between the resulting values, with the risk that the regressions are strongly influenced by extreme values. We tested therefore whether the above model or similar models can be confirmed by making subgroups of the river basins. To form the subgroups, the average climatic situation of the basins was selected. Figure 5 provides a plot of mean annual sediment concentration versus specific runoff intensity for all rivers investigated in this study, and the rivers are classified additionally according to their average climatic situation. Although concentrations scatter over more than three orders of magnitude, one can see that for a given runoff intensity, the rivers in dry climates (white fills) tend to have greater concentrations than the rivers in wet climates (black fills). Consequently, omitting the dry climate rivers from the regression in eq (7) does not significantly change the regression coefficient, and the correlation coefficient increases ($r = 0.93$). This indicates that the above presented parameter product is useful to predict sediment fluxes in wet climates, whereas in dry climates sediment fluxes may behave differently. Applied only to all wet grid points, eq (7) yields a global sediment flux of 14.10 Gt/yr, with a corresponding area of 68.9 $10^6 \times km^2$. Note also from figure 5 that the sediment concentrations of the wet climate rivers have the tendency to increase with increasing runoff intensities. Concentrations tend toward a value of about 1g/l. This concentration has been proposed by Probst and Sigha (1989) to be a limiting value in

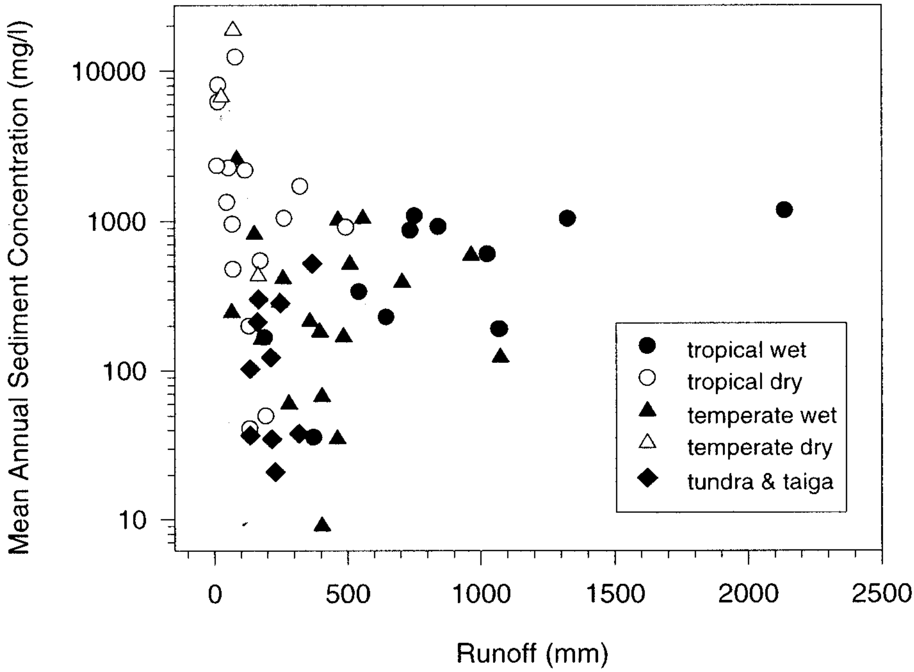

Fig. 5. Plot of mean annual sediment concentration versus mean annual drainage intensity for the river basins of table 1.

surface runoff waters. For the dry climate rivers, TSS concentrations have a tendency to decrease with increasing runoff intensities. Such behavior has also been reported by Probst and Amiotte-Suchet (1992) for rivers of the Maghreb region in North Africa.

Taking only the group of river basins that belong to the dry climates, no clear correlation between the observed sediment fluxes and environmental parameters or parameter combinations of the river basins can be found. This is also less surprising because the climatic variability can be great for these basins, making the average basin values extracted from the data sets less meaningful. The climatic grouping is based on the average basin situation, but in some basins classified as dry, the river hydrology can be strongly influenced by a particular part of the basin that has quite different environmental characteristics in comparison to the rest of the basin. For example, in the Colorado or Rio Negro river basins, less than 20 percent of the basins can be classified as wet, but according to the Q data set used in this study (see above) more than 70 percent of total runoff originates from these basin parts. Another reason that could additionally contribute to generally weaker correlation in the dry climate river group is the already mentioned fact that the literature estimates for these rivers are probably less reliable.

Table 6 lists the results when the regressions were performed within the individual climate groups of river basins. The temperate and the tropical dry climates were lumped together as one type named Dry Climates because only 2 rivers belong to the temperate dry climate (not considering the Huanghe River), and this number does not allow statistical analysis. For all three wet river groups, great correlation coefficients were found. In the tundra and taiga climate, both the products of Q, Slope, Four, and LithMI (P4) and of Q, Slope, and LithMI (P5) show the greatest correlation with sF_{TSS}. Four is probably not a very meaningful parameter in this climate type, because of the temporary storage of water as snow. Consequently, taking Four out of the parameter products does

TABLE 6

Regression of sediment yield versus several parameters and parameter products

Climate	Number of Rivers	Correlation Coefficient r					
		Q	*P2*	*P3*	*P4*	*P5*	*P6*
Tundra and Taiga	10	0.65	0.89	0.94	0.98	**0.98**	0.97
Temperate Wet	19	0.49	**0.83**	0.75	0.73	0.75	0.76
Tropical Wet	12	0.87	0.73	0.92	**0.96**	0.96	0.93
Dry Climates	17	0.80	0.55	0.79	**0.81**	0.55	0.63

Climate	Number of Rivers	Regression Coefficient m (f(x) = m × x)					
		Q	*P2*	*P3*	*P4*	*P5*	*P6*
Tundra and Taiga	10	0.22	*13.13*	0.037	0.00255	**0.125**	--
Temperate Wet	19	0.38	**16.52**	0.020	0.00119	0.114	1.97
Tropical Wet	12	*0.83*	26.70	0.020	**0.00081**	0.211	5.17
Dry Climates	17	1.18	25.73	*0.088*	**0.01176**	1.252	14.36

P2 = (Four × Slope); P3 = (Four × Slope × Q); P4 = (Four × Slope × Q × LithMI); P5 = (Slope × Q × LithMI); P6 = (Slope × Q)
The boldface regressions are selected as the best models (see text).
All regressions are significant at least with $P < 0.05$. The regression coefficient was calculated by forcing the regression to pass through the origin. It is only shown when the intercept was not significant in the regressions, which means that for the intercept $P > 0.1$ ($P > 0.05$ for the values in italics).

not decrease the correlation coefficient. Also in the tropical wet climate type, P4 and P5 yield the greatest correlation coefficients with sF_{TSS}. In the temperate wet climate, however, it is the product of Four and Slope (P2) that is best correlated with sediment fluxes, and neither the inclusion of Q nor of LithMI in any of the parameter combinations can improve the regressions with respect to this correlation.

One can suppose that Four should be especially important when strong precipitation falls on soils that are in an intermediate position between field capacity and extreme water limitation. This can then provoke a short-time overflow of the soils, which may enhance sheet erosion compared to a site with the same annual climatic characteristics, but where precipitation is more uniformly distributed over the year. Among the wet climate types, it is probably in the temperate wet climate where the condition that water limitation in the soils coincides with strong precipitation is the most often the case. In the tropical wet climate, for comparison, one should expect a greater water excess on average, and the soils should be closer to field capacity throughout the year.

When comparing the average situation for both climate types (fig. 6), it is interesting to note that in the temperate wet climate, greatest Four values fall together with a tendency toward a water limitation potential in the soils. The opposite is the case for the tropical wet climate type, where greatest Four are encountered when the soils should be at field capacity. This is indicating that seasonal variability of precipitation is probably less important in this climate (although Four naturally has greater absolute values on average in the tropical wet climate), and it could explain why Four is found in the regressions to be especially important in the temperate wet climate type.

However, an important question here is whether the parameter Four is at least not also partly correlated to precipitation intensity. Also this factor may naturally influence mechanical erosion rates in a drainage basin. One may speculate that an uneven precipitation distribution over the year (for example, the abundance of rain periods) may fall together with a high frequency of thunderstorms and thus also with great precipitation intensities. Additional parameters reflecting seasonal precipitation intensity are needed to test this.

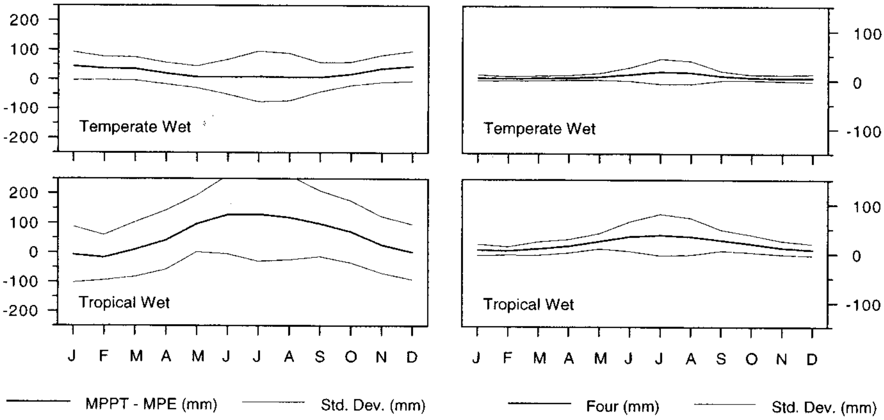

Fig. 6. Water limitation potential of the soils–as determined by the difference of monthly precipitation and monthly potential evapotranspiration (MPPT–MPE) in comparison with the distribution of Four in the temperate wet and the tropical wet climate types. The values are calculated on the basis of all continental grid points of the northern Hemisphere that fall into the climate types (the southern Hemisphere has been omitted because of the inversion of the seasons in both hemispheres). MPE was calculated according to Holdridge (1959).

For the group of dry climate river basins, the statistics in table 6 were performed in a different way. As mentioned above, great amounts of the total runoff in these basins can originate from small but quite humid parts of the basins, which may also influence considerably the total sediment fluxes in these basins. We calculated therefore for the wet basin parts of the dry climate rivers a theoretical sediment flux according to the most significant regression models found in the wet river groups (boldface regressions) and subtracted the values from the observed total sediment flux. The resulting F_{TSS} values were then used for regression with the basin characteristics, this time calculated on the basis of the dry grid points only in the basins. With such a procedure, P4 is also found to be best correlated with sediment fluxes, but note that the regression coefficients in nearly all regressions are much greater than for the corresponding regressions in the wet climate types (table 6). This means that erodibility in dry climates is much greater than in wet climates. One explanation for this could be that water limitation in dry climates leads to a vegetation cover that represents a much less efficient protection of the soils against mechanical erosion. Soil protection by vegetation is probably a threshold phenomenon rather than a continuous effect. There may exist a minimal vegetation cover density, below which mechanical erosion rates rapidly increase. Biomass density often strongly increases from dry to wet conditions. However, because we include modelled and observed F_{TSS} values in the regressions, the results presented here have to be taken with caution. More data especially of river basins that are dry over the complete basin area (monoclimatic) are needed to confirm such a trend.

Taking the boldface regressions of table 6, the global sediment flux to the oceans can be determined on the basis of the corresponding data sets used in this study. Figure 7 shows the corresponding xy-plots, and table 7 gives the resulting sediment budgets, regionalized for the different climate types, the different continents, and the different ocean basins. Because of the lack of additional data, the model for the tundra and taiga climate was also applied to the ice-free polar climate type in the budget calculations, and the model for the dry climates also the desert climate type. Although these two climate types cover considerable parts of the continents, they contribute very little to the total sediment flux (0.05 Gt/yr for the ice-free polar climate, and 0.03 Gt/yr for the desert climate). For the tropical wet climate, we preferred the sF_{TSS}-P4 model compared to the

sF_{TSS}-P5 model as the better one because of a slightly greater correlation coefficient for this regression. But note that taking the sF_{TSS}-P5 model instead would result in an extrapolated sediment flux only about 7 percent lower than the value calculated with the sF_{TSS}-P4 model. When extrapolated to the total continental area, our models yield a total

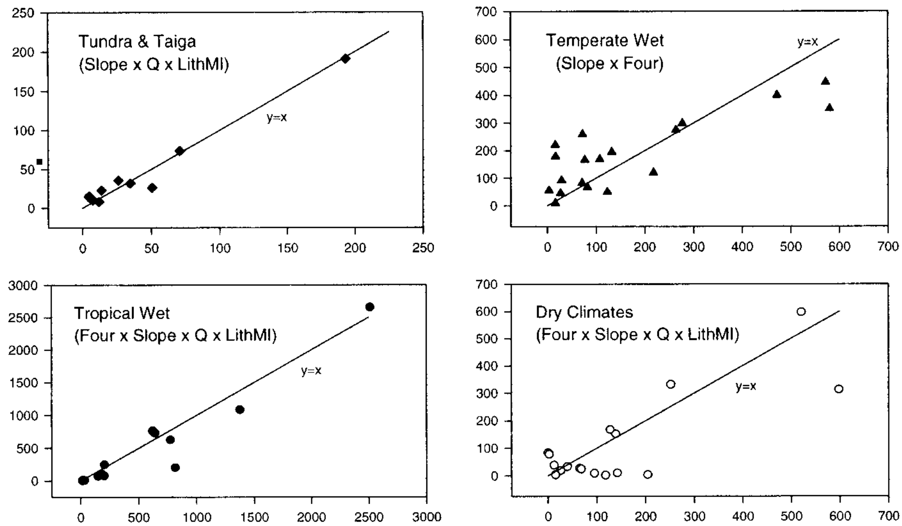

Fig. 7. Plot of predicted (y-axis) versus observed (x-axis) sediment yields (t km^{-2} yr^{-1}) according to the best correlated parameter products in table 6 (p. 281).

TABLE 7

Fluxes of water and of sediments from the continents to the oceans

	Drainage Area * (10^6 km^2)	Discharge # (km^3/yr)	sFTSS (t km^{-2} yr^{-1}) modelled	sFTSS (t km^{-2} yr^{-1}) modelled & corrected	FTSS (Gt/yr) modelled	FTSS (Gt/yr) modelled and corrected
Polar, without ice	3.892	762	13	8	0.049	0.032
Tundra & Taiga	23.232	6930	32	28	0.733	0.646
Temperate Dry	9.635	729	115	249	1.111	2.403
Temperate Wet	16.918	7753	183	195	3.100	3.300
Tropical Dry	21.790	3101	181	207	3.943	4.520
Tropical Wet	24.919	22403	235	204	5.858	5.090
Desert	5.940	66	5	7	0.027	0.044
Total	106.326	41744	139	151	14.822	16.035
Africa	18.288	4120	33	53	0.610	0.973
Europe	9.564	3079	103	88	0.989	0.841
North America	23.020	7142	92	136	2.122	3.138
South America	17.732	11150	161	166	2.857	2.940
Asia	32.518	15318	247	244	8.032	7.930
Australia	4.476	773	46	46	0.207	0.205
Antarctis	0.728	162	7	10	0.005	0.007
Total	106.326	41744	139	151	14.822	16.035
Arctic Ocean	16.982	3239	18	14	0.313	0.235
North Atlantic	27.300	13484	109	132	2.984	3.600
South Atlantic	16.959	5074	35	31	0.599	0.523
Pacific	21.025	13532	293	352	6.165	7.407
Indian Ocean	16.594	5166	243	214	4.029	3.556
Mediterranean	6.739	1087	108	105	0.725	0.708
below 60° South	0.728	162	7	9	0.005	0.007
Total	106.326	41744	139	151	14.822	16.035

* Without endoreic and glaciated regions.
\# According to Korzoun and others (1977)–see text.

sediment flux of about 14.82 Gt/yr discharged to the oceans. About 40 percent originated from the tropical wet climate, 21 percent from the temperate wet climate, 5 percent from the tundra and taiga climate, and 34 percent from dry climates (deserts, temperate dry, tropical dry).

Influence of lithology.–Summing the sediment fluxes for the wet climate types results in a value of only 9.74 Gt/yr, which is considerably lower than the value calculated with eq (7) for all wet continental grid points (14.82 Gt/yr, see above). This is due mainly to the fact that LithMI was included in the regressions both for the tundra and taiga climate and for the tropical wet climate. Taking instead for these two climates the sF_{TSS}-P3 regressions (that is using runoff intensity, seasonal precipitation variability, and basin slope), which have also still great correlation coefficients (table 6), the resulting sediment flux for the three wet climate types would increase to a value of 14.96 Gt/yr (tundra and taiga, 2.16 Gt/yr, temperate wet, 3.10 Gt/yr, tropical wet, 9.70 Gt/yr). In our data, lithologies that are less resistant to mechanical erosion are over-represented in the group of tropical wet rivers. For this reason an important question is whether the regressions would change with a set of tropical wet rivers with more variable lithologies. Probably too much weight is given to LithMI in our regression models. This is important because it could lead to a considerable underestimation of the total sediment budgets in table 7.

An assessment of the role of lithology on river sediment fluxes may be difficult in a study like ours, since it may depend strongly on the variable contributions of the different processes responsible for the sediment mobilization. The influence of lithology on mechanical erosion rates is probably great with respect to channel erosion but less important with respect to hill slope erosion because the outcropping lithologies are normally covered by the soils. Unfortunately, there is little known about the general contributions of channel erosion to total sediment fluxes, at least at the global scale. Kattan, Gac, and Probst (1987) estimated channel erosion for the Senegal River to be at least 20 percent of the total river transport, and Etchanchu and Probst (1986) found for the Girou River (a tributary of the Garonne River in France) a value of 30 percent.

Basin area and sediment storage.–In many studies, basin area was found to be negatively correlated with sediment yields (Milliman and Syvitski, 1992; Probst and Amiotte-Suchet, 1992; Probst, 1992), and certain authors even proposed basin area to be the most dominant controlling factor for sF_{TSS} (Milliman and Syvitski, 1992). The correlation matrix in figure 4 confirms the inverse relationship of A with sF_{TSS} at the global scale, but the correlation is weak, as this was also noted by Summerfield and Hulton (1994). In the literature, the effect of basin area on sediment yields has been explained in several ways. Among the most common arguments, it was mentioned that small basins generally exhibit steeper slopes and steeper stream gradients than large river basins (Wilson, 1973). The latter often have great areas with low slopes and low stream gradients especially in their downstream parts. Related to this, small basins tend to have limited flood plain development, so that most of the material eroded from the basin is just flushed out of the system, and little is deposited within the basin. Finally, Jansson (1982) noted also that the probability of an intense storm covering the whole of a river basin decreases with increasing basin size. For this reason, the maximum flood discharge per unit area should be inversely related to the size of the drainage area, and the capacity of the water flow to evacuate material deposited in a channel after local thunderstorms should be smaller for large basins than for small basins.

Basin area can therefore be regarded to sum up several factors that may influence sediment yields. Many of these factors are considered as individual parameters in this study, as is the case, for example, for Slope. Neglecting these factors, it is mainly the relationship between basin size and the sediment storage capacity of a drainage basin that has to be investigated more in detail. For this reason, we also grouped the river basins investigated in this study according to their basin size and repeated the regression analyses within the different subgroups in order to test whether the results are different in large compared to small basins. However, given the same hydroclimatic, morphological, and lithological characteristics, no clear indications were found that large basins are accompanied by enhanced sedimentation in the basins and thus a lower sediment delivery out of the basins (Ludwig, in press). This does not, of course, mean that there is no sedimentation in the basins. It implies that area only is an insufficient criterion to detect sediment storage in the basins. The abundance of internal reservoirs, especially of lakes, should be more important in this context (note that the lowest annual sediment concentration among the rivers of table 2 is observed for the St. Lawrence River, which has an important part of its basin area covered by lakes). It probably implies also that the factors controlling the erosion processes in drainage basins clearly dominate the processes controlling the sedimentation processes at the global scale.

Inverse correlation between sediment yields and basin area often reported in the literature may be in many cases due to the fact that mean basin slope also often decreases with increasing areas. Figure 8 shows the corresponding plot for the river basins investigated in this study. Although the overall correlation is only weak, one can see that greatest Slope values occur only in small basins and that there is a trend of smaller values with increasing basin area. In more regional studies, where the environmental variability of the investigated river basins is less important than in our study, such a trend may be more distinct (going from larger to smaller scales, especially climatic variability may be reduced while morphological variability is still important). It is also interesting to note in figure 8 that the dispersion of the points is especially great for the dry river basins. This may reflect the fact that in these basins considerable parts of the basin can be desert (Ludwig, Probst, and Kempe, 1996), making the basin areas quite variable.

Nevertheless, it must be stated that the process of sediment retention in river basins cannot be quantified on the basis of the data we used. Generally, it is possible that the budgets we calculated with our empirical models may represent lower estimates. Assuming that sedimentation can be important at least in some of the major river basins

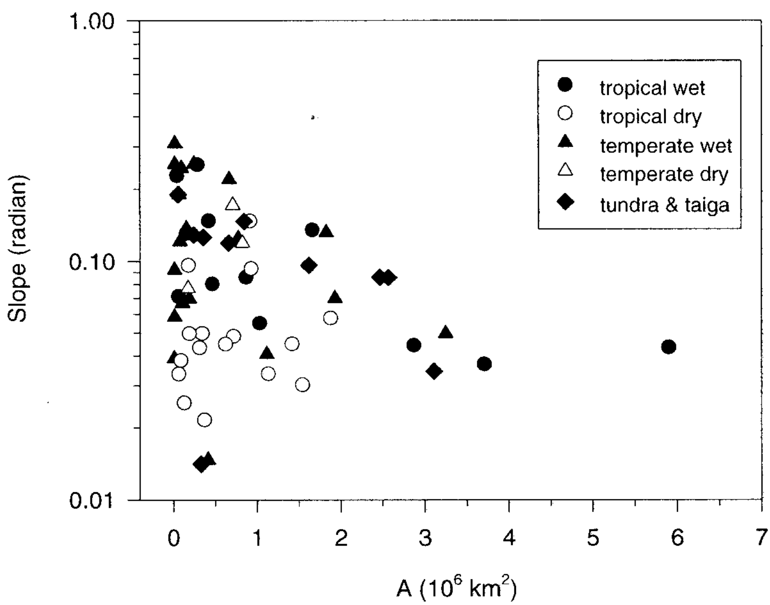

Fig. 8. Plot of mean basin slope versus basin area for the river basins of table 1.

considered in this study implies that some of the regression coefficients we determined can be too small to apply them to small river basins, where, on average, sediment retention should be less important. Most of the continental area where no sediment data are available consists in an increasing number of more and more small basins (Milliman and Syvitski, 1992).

SPATIAL DISTRIBUTION OF RIVER SEDIMENT FLUXES

The results of the previous sections indicate that present-day river sediment fluxes are mainly controlled by a combination of hydroclimatic, morphological, and lithological factors such as Q, Slope, Four, and LithMI. Our findings are in good agreement with the results of Phillips (1990) who found that slope gradient, runoff, and precipitation factors together should account for most of the global variation in soil erosion rates. It should be noted that the models presented here have a form similar to the Universal Soil Loss Equation (USLE) proposed by Wischmeier and colleagues (Wischmeier, Smith, and Uhland, 1958). Also the USLE includes rainfall intensity and slope as principal controlling factors, but additional parameters are needed for the USLE, including soil erodibility as a function of soil properties such as soil texture and the density and structure of the vegetation cover. The USLE was originally designed for local scale assessments of soil loss by rainfall from agricultural land, but the regression models presented in this study indicate that a similar approach could be applied in order to predict the variability of sediment yields also at global and regional scales.

Sediment yields on the continents.–When our empirical relationships are applied to the overall continental area in a 0.5° × 0.5° longitude/latitude grid point resolution on the basis of the corresponding data sets, it results in a global sediment yield map that depicts a regional variability in good agreement with field data. Low sediment yields are typical for the northernmost parts of the continents (north of 50°N) and naturally also for deserts. Greatest values are found for the humid regions in the south of Asia and in Oceania, as well as for the regions along young orogenic belts such as the Himalayas, the Andes, or the Alps. Because of the great values in young orogenic belts, it is interesting to compare the values resulting from our modelling with the study of Pinet and Souriau (1988) discussed above. When we combine the modelling with the distribution of continental crust ages depicted in figure 3, we calculate that about 10.4 Gt/yr of the global sediment flux originates from young orogenies (younger than 250 my) and 4.4 Gt/yr from old orogenies. These values are very close to the values we calculated with the relationships of Pinet and Souriau (eqs 1 and 2). Our study is therefore in agreement with theirs in terms of the estimated continental denudation rates but not in terms of the retained controlling factors for river sediment fluxes. Note that the great sediment yields along the young orogenic belts resulting from our modelling can have a twofold cause: on the one hand these regions are characterized by steep slopes, and on the other hand runoff intensity can be great because the mountain chains form barriers for the atmospheric water circulation, leading to enhanced precipitation.

Nevertheless, the outstanding sediment yields for the Huanghe and the Tana rivers manifest that the modelling approach cannot account for all local particularities documented by field data. Another problem is the lower reliability of the regression models for the dry climate rivers compared to the wet climate rivers (see above). We created therefore a second sediment yield map by using the modelled values as an interpolation matrix to distribute the observed sediment fluxes for the river basins of table 2 over the continents. This means that within the borders of the river basins we corrected all grid point values according to:

$$sF_{TSS}(\text{corrected}) = sF_{TSS}(\text{modelled}) \times sF_{TSS}(\text{basin average, observed})/sF_{TSS}(\text{basin average, modelled}) \quad (8)$$

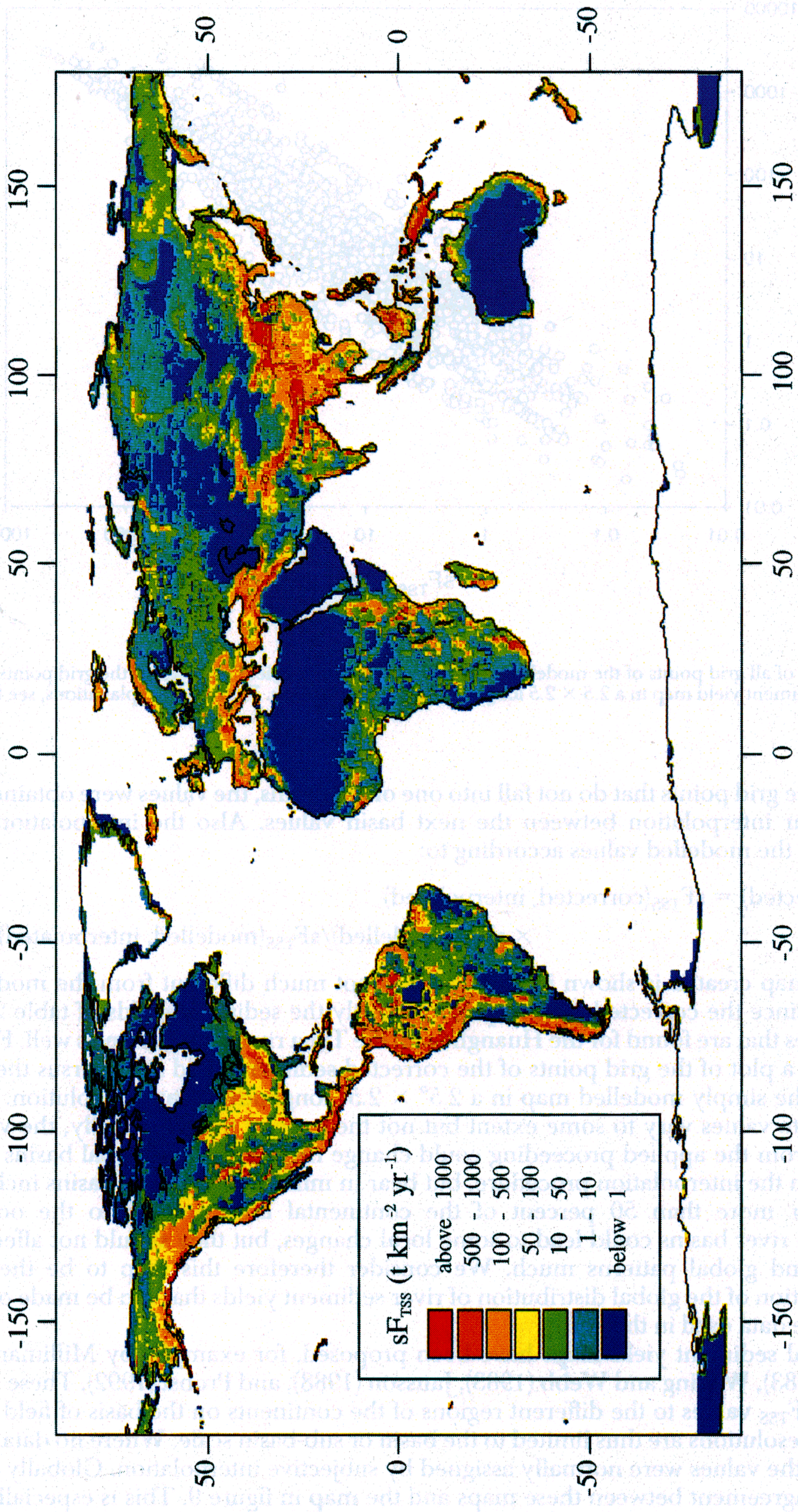

Fig. 9. Spatial distribution of river sediment yields on the continents.

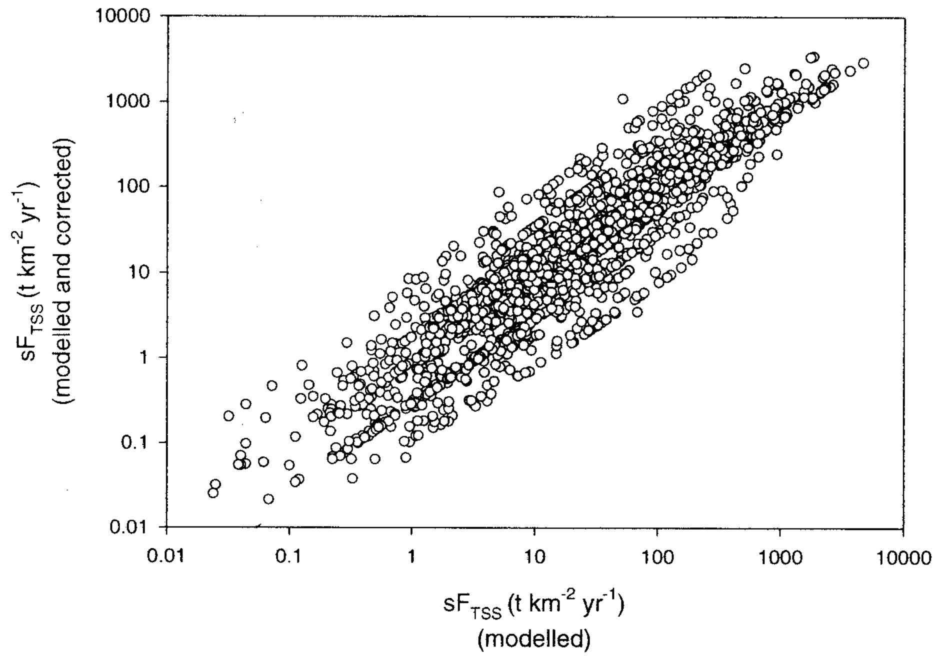

Fig. 10. Plot of all grid points of the modelled and corrected sediment yield map versus the grid points of the modelled sediment yield map in a 2.5 × 2.5 longitude/latitude resolution. For further explanations, see text.

For the grid points that do not fall into one of the basins, the values were obtained by a triangular interpolation between the next basin values. Also the interpolation was coupled to the modelled values according to:

$$sF_{TSS}(\text{corrected}) = sF_{TSS}(\text{corrected, interpolated}) \times sF_{TSS}(\text{modelled})/sF_{TSS}(\text{modelled, interpolated}) \quad (9)$$

The map created is shown in figure 9. It is not much different from the modelled map, but since the corrected map respects perfectly the sediment yields of table 2, the great values that are found for the Huanghe and the Tana rivers are shown as well. Figure 10 depicts a plot of the grid points of the corrected sediment yield map versus the grid points of the simply modelled map in a 2.5° × 2.5° longitude/latitude resolution. Note the absolute values vary to some extent but not the general trends. Locally, the values resulting from the applied proceeding could change naturally if additional basins were included in the interpolation procedure, but bear in mind that the river basins included here cover more than 50 percent of the continental area drained to the oceans. Additional river basins could lead to some local changes, but they should not affect the regional and global patterns much. We consider therefore this map to be the best representation of the global distribution of river sediment yields that can be made on the basis of the data used in this study.

Global sediment yield maps have been proposed, for example, by Milliman and Meade (1983), Walling and Webb (1983), Jansson (1988), and Probst (1992). These maps assigned sF_{TSS} values to the different regions of the continents on the basis of field data, and their resolutions are thus limited to the basin or sub-basin scale. Where no data were available, the values were normally assigned by subjective interpolation. Globally there is a good agreement between these maps and the map in figure 9. This is especially the case for the map of Walling and Webb, which is more detailed than, for example, the map of Probst.

Also the sediment budgets resulting from figure 9 have been added in table 7. The comparison of the pure modelling approach and the combined modelling/interpolation approach is interesting, because it can help to identify the regions where the modelling deviates the most from observations. Note also, however, that the interpolation approach is not without problems, because it has a tendency to extend local phenomenons to larger scales, which might not be true in all cases. The most striking difference between the maps is the fact that in the corrected map the sediment contributions from the dry climate types increase considerably, whereas the contribution of the tropical wet climate decreases. The tropical dry climate is now nearly of the same importance for the global sediment flux as the tropical wet climate, although the runoff contribution from the tropical dry climate is only less than 15 percent of the runoff contribution from the wet tropical climate. A part of the increased sediment contribution from the dry climates is naturally related to the fact that the Huanghe and the Tana rivers are included in the corrected map (both rivers belong to dry climate types), but the values also increased in other dry climate regions (for example, in North America). This underlines the importance of additional investigations on the controls of river sediment fluxes, especially in dry climates.

One has also to mention that both maps (modelled as well as modelled and interpolated) tend to smooth local variability. One of the shortcomings of our modelling is that it cannot account for sediment storage in the basins. When there is storage in one part of the basin, more must be eroded in another part of the basin to yield the average sediment flux observed at the river mouth. Another smoothing effect could be related to the limited grid point resolution of the data sets, which probably cuts off extremes by averaging the values. An idea of the possible extent of smoothing can be obtained by looking in detail at the Amazon Basin, where sediment yields have also been studied at the sub-basin level. Gibbs (1967) and Meade and others (1985) reported that at least 80 percent of the sediments transported by the Amazon River originate from the Andes. In the two maps we created, only about 60 percent of the total sediment load of the Amazon comes from regions with elevations >500 m. These regions cover about 13 percent of the total basin area and represent mainly the Andes.

Taking the values of the corrected map as the best estimates, global sediment delivery to the oceans is about 16 Gt/yr. The specific sediment export from Asia, the continent with the greatest average sediment yield, is about 5 times greater than from Africa or from Australia, the continents with the lowest average sediment yields. It is also interesting to note from the values in table 7 that the average sediment yields for temperate wet, temperate dry, tropical wet, and tropical dry climate types are quite similar (varying from about 200-250 t km^{-2} yr^{-1}). The values are considerably lower only for the other climate types. This again indicates that in order to predict the variability of river sediment yields at the global scale, climate alone is obviously not very meaningful.

River sediment delivery to the oceans.–Table 7 also shows that the Pacific and the Indian Ocean together receive by far the bulk of the global sediment delivery: about 68 percent of the global river sediment load to the sea can be attributed to these two oceans. Milliman and Meade (1983) estimated that up to 70 percent of the world sediment transport may originate from southern Asia and the larger islands of Oceania. The map in figure 9 agrees with the dominant role of these regions for the global budget, but since the 68 percent mentioned correspond to the entire Pacific and Indian oceans, this indicates that the importance of these regions is probably not as great as estimated by Milliman and Meade.

It is also interesting to look, in more detail, at the spatial distribution of the river sediment discharge to the oceans. For a prediction of the local inputs of sediments into the oceanic system in a grid point resolution, we combined our global sediment yield map shown in figure 9 with a river routing file that has been created by Miller, Russel, and Caliri (1994) in a 2° × 2.5° latitude/longitude grid point resolution. The routing file allows us to attribute an oceanic grid point to each grid point on the continents to which they are drained in the same resolution as the river routing file. In a previous study we presented the global river inputs of inorganic and organic carbon in the same way (Ludwig, Amiotte-Suchet, and Probst, 1996).

Figure 11 shows the resulting map of river sediment fluxes to the sea, and figure 12 summarizes the holospheric distribution of these fluxes for the different ocean basins. Because of the great differences in size of the rivers discharging to the oceans, variability between the values for the different oceanic grid points is naturally great. More than 82 percent of the total sediment delivery enters the sea in the northern hemisphere. Locally, the inflow of certain rivers can have a great influence on the regional budgets, as is the case, for example, for the Amazon River into the Atlantic Ocean, for the Ganges/Brahmaputra into the Indian Ocean, or for the Huange and Chanjiang rivers into the Pacific Ocean. Taking the grid elements from 60° to 160°E longitude and 14°S to 46°N latitude to represent Oceania as well as the south and southeast of Asia, we calculate that about 46 percent of the global sediment flux enters the oceans in this part of the world. This is considerably lower than the above mentioned 70 percent estimated by Milliman and Meade (1983). Nevertheless, since this corresponds to only about 14 percent of the global drainage area, it still underlines the important role of this region for the global river sediment budgets.

CONCLUSIONS

Up to now, several attempts have been made to relate the variability of river sediment yields to the variability of the environmental parameters characterizing the corresponding river basins. Some of these attempts were briefly reviewed on the previous pages. Although generalizations naturally have to be made with caution, we have seen from the literature review that the models based simply on climatic controlling parameters tend to overestimate the global sediment delivery to the oceans, whereas models based purely on morphological parameters tend to underestimate the global sediment flux. Consequently, the results of our study show that it is the combination of different factors that yields the most significant regression models. Sediment yields are best correlated by forming the products of a number of hydroclimatic, geomorphological, and lithological factors, that is runoff intensity (Q), the steepness of morphology (Slope), an index characterizing the seasonal precipitation variability (Four), and an index characterizing the softness of lithology with respect to mechanical erosion (LithMI). The best correlated parameter combination varies to some extent when the rivers are grouped according to their average climatic situation, but it is always a combination of the above parameters that yields greatest correlation coefficients.

When our models are applied to the total continental area, they produce a map of the regional variability of river sediment yields in good agreement with field data. By far the greatest values are found in the young orogenic belts of the continents. This is in agreement with previous studies (such as the one of Pinet and Souriau, 1988), although we have shown that it is not orogeny itself that leads to that elevated values but rather the combination of the climatic and morphological particularities in these regions. We also showed that with the same controlling factors, the regression coefficients are greater in the dry than in the wet climates, even if it is more difficult to establish relationships for the dry climate rivers because of the great environmental heterogeneity that is often typical in these basins. This indicates a much greater susceptibility of dry climate regions to mechanical erosion, which was postulated by many previous studies (for example, Langbein and Schumm, 1958). One reason for a greater erodibility of the soils in these

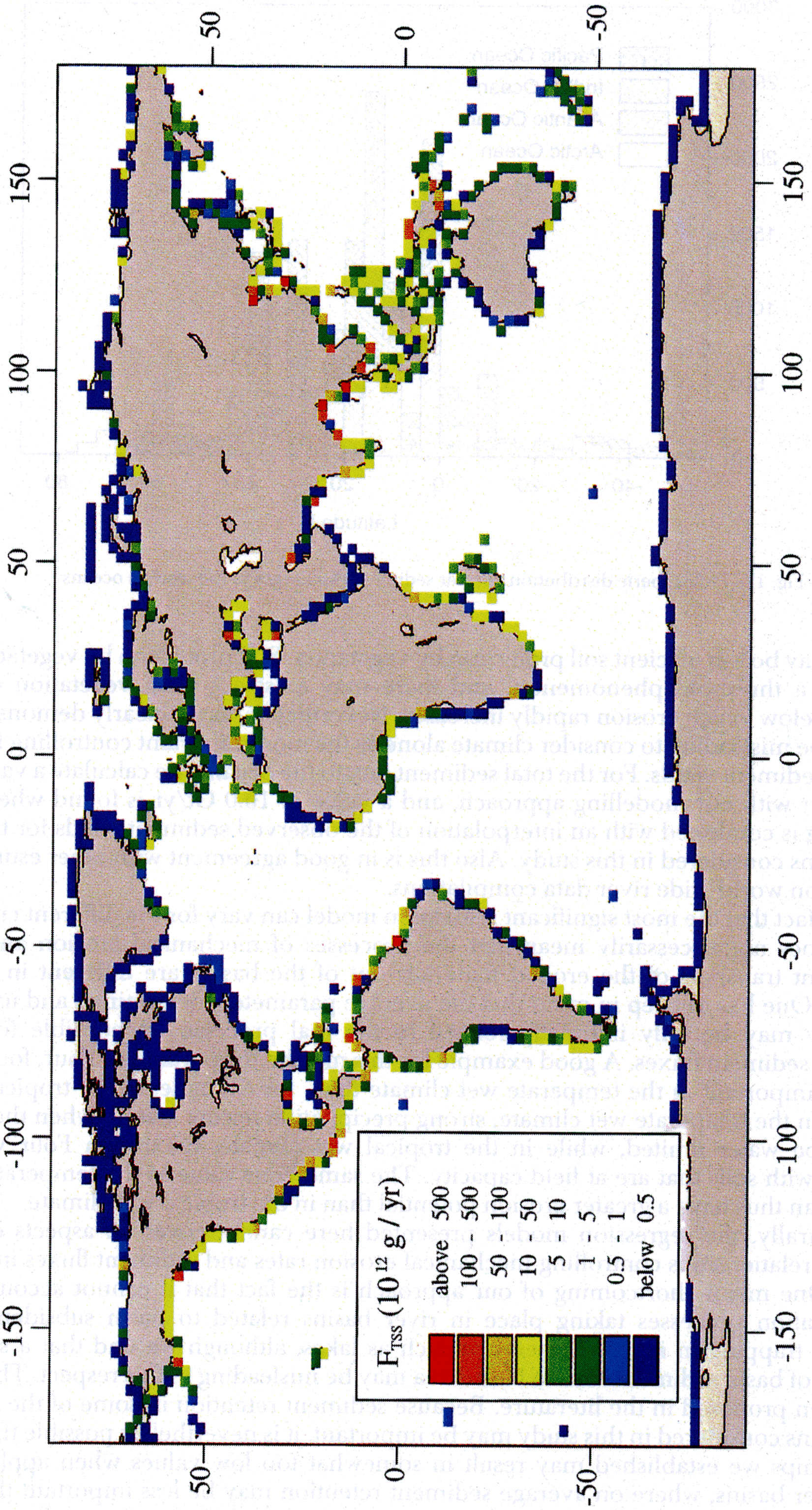

Fig. 11. Global discharge of river sediments to the world's oceans.

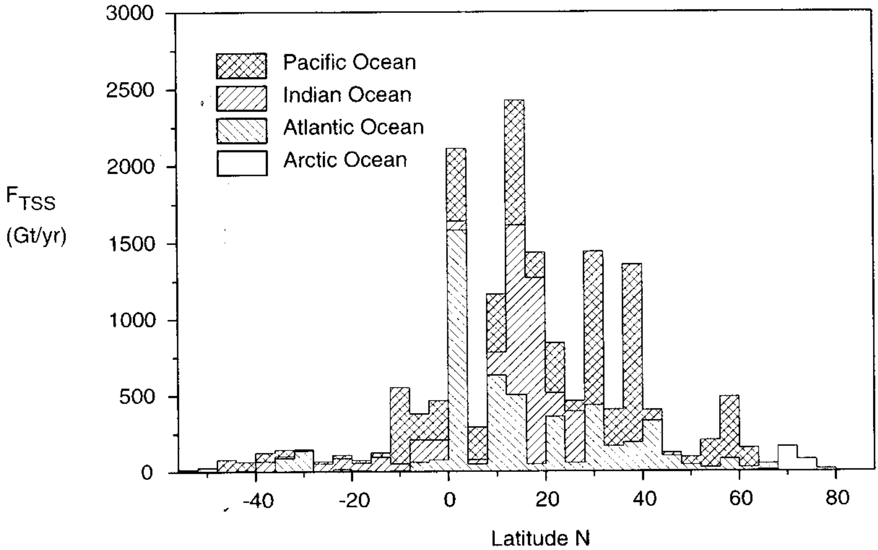

Fig. 12. Holospheric distribution of river sediment discharges to the world's oceans.

regions may be less efficient soil protection by vegetation. Soil protection by vegetation is probably a threshold phenomenon, and there may exist a certain vegetation cover density, below which erosion rapidly increases. Nevertheless, as we clearly demonstrate, it would be misleading to consider climate alone as the most important controlling factor for river sediment yields. For the total sediment flux to the oceans, we calculate a value of 14.8 Gt/yr with our modelling approach, and a value of 16.0 Gt/yr is found when the modelling is combined with an interpolation of the observed sediment yields for the 60 river basins considered in this study. Also this is in good agreement with other estimates based upon world-wide river data compilations.

The fact that the most significant regression model can vary for the different climate groups does not necessarily mean that the processes of mechanical erosion and the subsequent transport of the eroded materials out of the basins are different in these climates. One has to keep in mind that the average parameters determined and used in our study may be only indirectly related to the real processes responsible for the observed sediment fluxes. A good example for this may be the parameter Four, found to be more important in the temperate wet climate than, for example, in the tropical wet climate. In the temperate wet climate, strong precipitation occurs mainly when the soils tend to be water limited, while in the tropical wet climate, maximum Four values coincide with soils that are at field capacity. The same Four value in the temperate wet climate can thus have a greater erosion potential than in the tropical wet climate.

Naturally, the regression models presented here cannot cover all aspects of the complex relationships controlling mechanical erosion rates and sediment fluxes in river basins. One major shortcoming of our approach is the fact that it cannot account for sedimentation processes taking place in river basins related to basin subsidence or sediment trapping in internal reservoirs such as lakes, although we find that a simple coupling of basin sedimentation to basin area may be misleading in this respect. This has often been proposed in the literature. Because sediment retention in some of the major river basins considered in this study may be important, it is nevertheless possible that the relationships we established may result in somewhat too low values when applied to small river basins, where on average sediment retention may be less important than in great basins. Given the fact that most parts of the continents where sediment data are lacking consist of small basins implies that the 16 Gt/yr we determined as overall riverine sediment delivery to the oceans is rather a lower estimate. In fact, Milliman and Syvitski (1992) estimated a global riverine sediment flux of 20 Gt/yr based on a much larger number of rivers and including more smaller southeastern Asian and Ocean rivers.

For this reason it would be interesting to do a similar study as ours but on the basis of data for small rivers only. This would also have the advantage that mean environmental basin characteristics are naturally more meaningful for small basins than for large ones. As we clearly show for the basins of the dry climates, average basin values can be misleading in identifying the principal controlling factors for river sediment fluxes. Unfortunately, small rivers have often been overlooked up to now for long-term monitoring of sediment loads, and the scarcity of available data makes it difficult to do a global scale approach similar to our study.

Further studies may focus especially on river sediment fluxes in arid climates. In our data, dry climate rivers that are monoclimatic over most of their basin area are underrepresented, and additional data are needed to confirm the detected trends. This is important because it can influence considerably the global and regional budgets. Another point for further research could be the determination of additional parameters that better describe the seasonal patterns in the river basins. As far as reliable water budget models that can predict the variability of the water content in the soils over the year may be available, it would be interesting, for example, to quantify the amount of strong precipitation only when the soils are water limited. This may be more meaningful than the parameter Four tested here. Also the role of lithology on river sediment fluxes should be further investigated with additional data, since we have seen that omitting lithology (LithMI) in the parameter products leads also to quite high correlation coefficients, but the corresponding regression models predict considerably greater sediment fluxes at global and regional scales. Finally, for the extrapolation of the presented relationships to other than present-day conditions, more should be known about the role of catastrophic events for the global fluxes. There is some evidence from the geological record that such events may have had a considerable influence on global sediment fluxes during geological times (Milliman and others, 1996).

ACKNOWLEDGMENTS

This work was supported by funding by the Commission of the European Communities within the project European Study on Carbon in the Oceans, the Biosphere, and the Atmosphere (ESCOBA)–Terrestrial Biosphere, (contract EV5V CT 92 0119). We are especially grateful to the Société de Secours des Amis des Sciences (Paris) for their support by awarding a doctorate grant to Wolfgang Ludwig, to Dr. J. Miller from the Institute of Marine and Coastal Science, Rutgers University for the river routing files, as well as to John Milliman and an anonymous reviewer for their constructive reviews of the manuscript.

REFERENCES

Ahamer, G., Spitzer, J., Weiss, C.O., and Fankhauser, G., 1992, Der Einfluβ einer verstärkten energetischen Biomassennutzung auf die CO_2-Konzentration in der Atmosphäre: Graz, Institut für Energieforschung, Joanneum Research, Abschlussbericht, 540 p.

Ahnert, F., 1970, Functional relationships between denudation, relief and uplift in large mid-latitude drainage basins: American Journal of Science, v. 268, p. 243–263.

Amiotte-Suchet, P., 1995, Cycle du carbone, érosion chimique des continents et transferts vers les océans. Strasbourg, Sciences Géologiques, Mémoire 97, 156 p.

Amiotte-Suchet, P., and Probst, J.L., 1993a, Modeling of atmospheric CO_2 consumption by chemical weathering of rocks: Application to the Garonne, Congo and Amazon basins: Chemical Geology, v. 107, p. 205–210.

—— 1993b, Flux de CO_2 consommé par altération chimique continentale: influence du drainage et de la lithologie: Académie des Sciences, Comptes Rendus, Paris, v. 317, p. 615–622.

—— 1995, A global model for present day atmospheric/soil CO_2 consumption by chemical erosion of continental rocks (GEM-CO_2): Tellus, v. 47B, p. 273–280.

Burchfiel, B.C., 1983, The continental crust: Scientific American, v. 249, p. 86–98.
Cadée, G.C., 1987, Organic carbon in the Ems River and estuary: A comparison of summer and winter conditions, *in* Degens, E.T., Kempe, S., and Gan Wei-Bin, editors, Transport of Carbon and Minerals in Major World Rivers, Part 4: Mitteilungen des Geologisch-Paläontologischen Institutes der Universität Hamburg, SCOPE/UNEP Sonderband. 64, Hamburg, p. 359–374.
Charania, S.H., 1988, A strategy for organizing a sediment data collection network based on the available hydrological records for a catchment in Kenia, *in* Bordas, M.P., and Walling, D., editors, Sediment Budgets. Proceedings of the Porto Alegre Symposium: Wallingford, Michigan, IAHS Publication, 174, IAHS Press, p. 181–195.
Claussen, M., Lohman, U., Roeckner, E., and Schulzweida, U., 1994, A global data set of land-surface parameters: Hamburg, Max-Planck-Institut für Meteorologie, MPI Report 135, 23 p.
CORINE, 1992, Soil Erosion Risk and Important Land Resources in the Southern Regions of the European Community: Brussels, Office for Official Publications of the European Communities, Report EUR 13233, 99 p.
Douglas, I., 1967, Man, vegetation, and the sediment yield of rivers: Nature, v. 215, p. 925–928.
Etchanchu, D., and Probst, J.L., 1988, Evolution of the chemical composition of the Garonne river water during the period 1971–1984: Hydrological Science Journal, v. 33, p. 243–256.
FNOC (Fleet Numerical Oceanography Center), 1992, Global elevation, terrain, and surface characteristics. Digital raster on a 10 minute geographic (lat/long) 1080 × 2160 grid, *in* NOAA/National Geophysical Data Center, Global Ecosystems Database, Version 1.0 Disc (CD-ROM): Boulder, Colorado, National Geophysical Data Center.
Fournier, F., 1960, Climat et érosion: Paris, Presses Universitaires de France, 201 p.
Gibbs, R.J., 1967, The geochemistry of the Amazon river system, the factors that control the salinity and composition and concentration of suspended solids: Geological Society of America Bulletin, v. 78, p. 1203–1232.
Global Runoff Data Centre Koblenz, 1991, Flow rates of selected world rivers: A database (DS 552.0): Boulder, Colorado, National Center for Atmospheric Research (NCAR).
Holdridge, L.R., 1947, Determination of world plant formations from simple climatic data: Science, v. 105, p. 367–368.
—— 1959, Simple method for determining potential evapotranspiration from temperate data: Science, v. 130, p. 572.
Holeman, J.N., 1968, The sediment yield of major rivers of the world: Water Resources Research, v. 4, p. 737–747.
International Geosphere Biosphere Program (IGBP), 1995, Implementation Plan, *in* Pernetta, J.C., and Milliman, J.D., editors, Land-Ocean Interactions in the Coastal Zone: Stockholm, IGBP Report No. 33, 215 p.
Jansen, J.M.L., and Painter, R.B., 1974, Predicting sediment yield from climate and topography: Journal of Hydrology, v. 21, p. 371–380.
Jansson, M.B., 1982, Land erosion by water in different climates: Uppsala University, UNGI Report 57, 151 p.
—— 1988, A global survey of sediment yield: Geografiska Annaler, v. 70, A, p. 81–98.
Kattan, Z., Gac, J.Y., and Probst, J.L., 1987, Suspended sediment load and mechanical erosion in the Senegal Basin–Estimation of the surface runoff concentration and relative contributions of channel and slope erosion: Journal of Hydrology, v. 92, p. 59–76.
Köppen, W., 1936, Das geographische System der Klimate, *in* Köppen, W., and Geiger, R., editors, Handbuch der Klimatologie, Band 1, Teil C. p. 1–44.
Korzoun, V.I., Sokolov, A.A., Budyko, M.I., Voskresensky, G.P., Kalinin, A.A., Konoplyantsev, E.S., Korotkevich, E.S., and Lvovich, M.I., 1977, Atlas of World Water Balance: Paris, UNESCO Press, 36 p.
Langbein, W.B., and Schumm, S.A., 1958, Yield of sediment in relation to mean annual precipitation: American Geophysical Union Transactions, v. 39, p. 1076–1084.
Leenheer, J.A., 1991, Organic substance structures that facilitate contaminant transport and transformations in aquatic sediments, *in* Baker, R.A., editor, Organic Substances and Sediments in Water, I, Humics and Soils: Chelsea, Michigan, Lewis Publishers, p. 3–21.
Legates, D.R., and Willmott, C.J., 1992, Monthly average surface air temperature and precipitation: Digital raster on a 30 minute geographic (lat/long) 360 × 720 grid, *in* NOAA/National Geophysical Data Center, editor, Global Ecosystems Database, Version 1.0 Disc (CD-ROM): Boulder, Colorado, National Geophysical Data Center.
Lesack, L.R., Hecky, R.E., and Melack, J.M., 1984, Transport of carbon, nitrogen, phosphorus, and major solutes in the Gambia River, West Africa: Limnology and Oceanography, v. 29, p. 816–830.
Ludwig, W., 1998, Continental erosion and river transport of organic carbon to the world's oceans: Strasbourg, Sciences Géologiques, Mémoire, in press.
Ludwig, W., Amiotte-Suchet, P., Munhoven, G., and Probst, J.L., 1998, Atmospheric CO_2 consumption by continental erosion: Present-day controls and implications for the last glacial maximum: Global and Planetary Change, in press.
Ludwig, W., Amiotte-Suchet, P., and Probst, J.L., 1996, River discharges of carbon to the world's oceans: determining local inputs of alkalinity and of dissolved and particulate organic carbon: Académie des Sciences, Comptes Rendus, Paris, v. 323, p. 1007–1014.
Ludwig, W., Probst, J.L., and Kempe, S., 1996, Predicting the oceanic input of organic carbon by continental erosion: Global Biogeochemical Cycles, v. 10, p. 23–41.
Meade, R.H., Dunne, T., Richey, J.E., Santos, U.d.M., and Salati, E., 1985, Storage and remobilization of suspended sediment in the lower Amazon River of Brazil: Science, v. 228, p. 488–490.
Meade, R.H., and Parker, R.S., 1985, Sediments in rivers of the United States: U.S. Geological Survey Water Supply Paper, v. 2275, p. 49–60.

Meybeck, M., ms, 1984, Les fleuves et le cycle géochimique des éléments. Paris, Thèse d'Etat Sciences, Université. VI, 558 p.
Miller, J.R., Russell, G.L., and Caliri, G., 1994, Continental-scale river flow in climate models: Journal of Climate, v. 7, p. 914–928.
Milliman, J.D., and Meade, R.H., 1983, World-wide delivery of river sediment to the oceans: Journal of Geology, v. 91, p. 1–21.
Milliman, J.D., Qin Yun-Shan, Ren Mei-E, and Saito, Y., 1987, Man's influence on the erosion and transport of sediment by Asian rivers: The Yellow River (Huanghe) example: Journal of Geology, v. 95, p. 751–762.
Milliman, J.D., Rutkowski, C., and Meybeck, M., 1995, River discharge to the sea. A global river index (GLORI): Texel, the Netherlands, LOICZ Core Project Office, 125 p.
Milliman, J.D., Snow, J., Jaeger, J., and Nittrouer, C., 1996, Catastrophic discharge of fluvial sediment to the ocean: evidence of Jøkulhlaup events in the Alsek Sea Valley, southeast Alaska (USA), *in* Walling, D.E., and Webb, B.W., editors, Erosion and Sediment Yield: Global and Regional Perspectives. Proceedings on the Exeter Symposium: Wallingford, Michigan, IAHS Publication. 236, IAHS Press, p. 367–379.
Milliman, J.D., and Syvitski, J.P.M., 1992, Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers: Journal of Geology, v. 100, p. 525–544.
Moore, J.G., and Mark, R.K., 1986, World slope map: EOS, v. 67, p. 1353–1356.
Ohmori, H., 1983, Erosion rates and their relation to vegetation from the viewpoint of world-wide distribution: University of Tokyo, Department of Geography Bulletin, v. 15, p. 77–91.
Olson, J.S., Watts, J.A., and Allison, L.J., 1983, Carbon in live vegetation of major world ecosystems: Oak Ridge, Tennessee, Oak Ridge National Laboratory, Report ORNL-5862, 164 p.
——— 1985, Major world ecosystem complexes ranked by carbon in live vegetation: A database: Oak Ridge, Tennessee, Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center, Report NDP-017, 19 p.
Phillips, J.D., 1990, Relative importance of factors influencing fluvial soil loss at a global scale: American Journal of Science, v. 290, p. 547–568.
Pinet, P., and Souriau, M., 1988, Continental erosion and large scale relief: Tectonics, v. 7, p. 563–582.
Probst, J.L., ms, 1983, Hydrologie du bassin de la Garonne, modèle de mélanges, bilans de l'érosion, exportation des phosphates et des nitrates: Toulouse, Ph.D. thesis, Université Paul Sabatier, 148 p.
——— 1992, Géochimie et hydrologie de l'érosion continentale. Mécanismes, bilan global actuel et fluctuations au cours des 500 derniers millions d'années: Strasbourg, Sciences Géologiques, Mémoir 94, 161 p.
Probst, J.L., and Amiotte-Suchet, P., 1992, Fluvial suspended sediment transport and mechanical erosion in the Maghreb (North Africa): Hydrological Science Journal, v. 37, p. 621–637.
Probst, J.L., and Bazerbachi, A., 1986, Transports en solution et en suspension par la Garonne supérieure: Strasbourg, Sciences Géologiques, Bulletin, v. 39, p. 79–98.
Probst, J.L., and Sigha, N., 1989, Estimation de l'écoulement superficiel et de sa charge en suspension sur quelques grands bassins fluviaux du monde: Académie des Sciences, Comptes Rendus, Paris, v. 309, p. 357–363.
Schumm, S.A., and Hadley, R.F., 1961, Progress in the application of landform analysis in studies of semi-arid erosion: United States Geological Survey Circular 437
Summerfield, M.A., 1991, Rates of uplift and denudation, *in* Summerfield, M.A., editor, Global Geomorphology: Singapore, Longman Scientific Publications, p. 371–402.
Summerfield, M.A., and Hulton, N.J., 1994, Natural controls of fluvial denudation rates in major world drainage basins: Journal of Geophysical Research, v. 99, B7, p. 13871–13883.
Vörösmarty, C.J., Meybeck, M., Fekete, B., and Sharma, K., 1997, The potential impact of neo-Castorization on sediment transport by the global network of rivers, *in* Walling, D.E., and J.-L. Probst, editors, Human Impact on Erosion and Sedimentation: Wallingford, Michigan, Proceedings of the Rabat Symposium, IAHS Publication, 245, IAHS Press, p. 261–273.
Walling, D.E., and Webb, B.W., 1983, Patterns of sediment yield, *in* Gregory, K.J., editor, Background to Palaeohydrology: New York, Wiley, p. 69–100.
——— 1985, Estimating the discharge of contaminants to coastal waters by rivers: Some cautionary comments: Marine Pollution Bulletin, v. 16, p. 488–492.
Webb, R.S., Rosenzweig, C.E., and Levine, E.R., 1991, A global data set of soil particle size properties, Washington, D.C., NASA Technical Memorandum # 4286, 33 p.
Wilson, L., 1973, Variations in mean annual sediment yield as a function of mean annual precipitation: American Journal of Science, v. 273, p. 335–349.
Wischmeier, W.H., Smith, D.D., and Uhland, R.E., 1958, Evaluation of factors in the soil loss equation: Agricultural Engineering, v. 39, p. 458–474.
Zobler, L., 1986, A world soil file for global climate modeling: NASA Technical Memorandum, # 87802.